A STUDY OF MODULATION WITH PARTICULAR EMPHASIS ON SUPPRESSOR-GRID MODULATION

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of
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by

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STUDY AND TYPES OF MODULATION

Radio telephony had been known for several years, but it was not until about 1921 that general broadcasting was introduced. It was the great demand for programs of an entertaining nature that caused radio engineers to study modulation in all its phases.

Modulation in its simplest form consists of the alterations of a radio frequency wave by the introduction of an audio frequency component.

There are at least two types of modulated waves; namely, amplitude modulated, and frequency modulated.

An amplitude modulated wave may be described as follows:

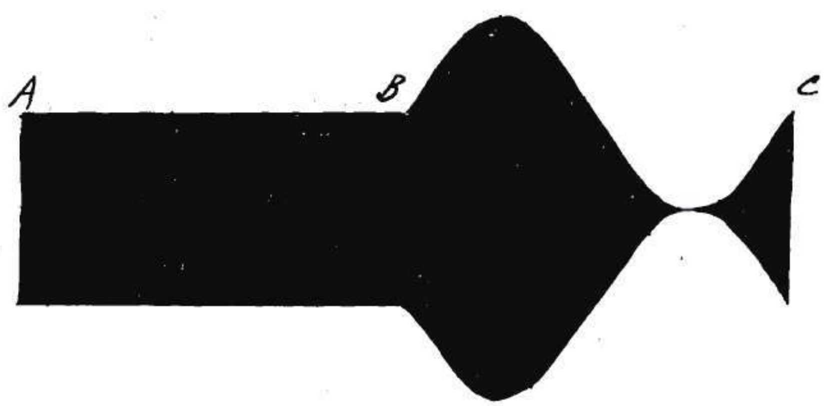


Figure 1.

In Figure 1, the portion A to B is the radio frequency carrier, or unmodulated wave, whose amplitude is constant. The portion B to C has a sine wave of audio frequency impressed upon the radio frequency in a manner that causes the peaks to be twice the height of the radio frequency wave alone, and the troughs to touch the zero axis. The wave then is said to be completely or 100% modulated. At the present time amplitude modulation is used almost exclusively for A3[1] emission below twenty megacycles.

A frequency modulated wave may be explained as a sine wave whose frequency is periodically varied about a mean frequency without increasing or decreasing the amplitude. Figure 2 shows a graphical illustration of this type of wave.

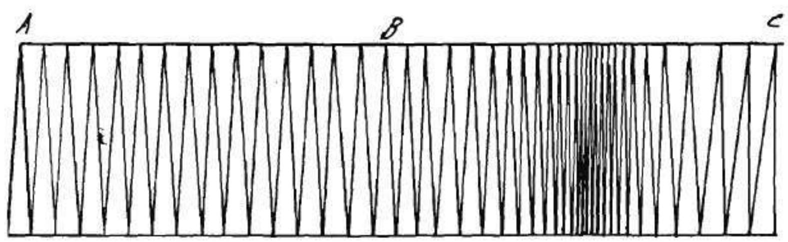


Fig. 2

The portion A to B is a sine wave without modulation, while the portion B to C is a complete audio cycle of a frequency modulated wave. If f_o is the carrier frequency f_s is the audio frequency of the modulator, the resultant wave contains components having frequencies of f_o, $f_o + f_s$, $f_o - f_s$, $f_o + 2f_s$, $f_o - 2f_s$, etc. It can, therefore, be seen that the band of frequencies is at least as great as that of amplitude modulation, and is probably somewhat greater. Due to the limited use of frequency modulation at the present, this treatise will be limited to applications and studies of amplitude modulated radio frequency waves.

[1]General Radio Regulations, annexed to the International Telecommunication Convention, Article 5, Page 184-5.

THE USE OF THE OSCILLOGRAPH IN STUDYING MODULATION

The oscillograph is a very useful instrument in the study of modulation, and for that reason a brief review of the images obtained is given herein. The figures 3 to 8, inclusive, show the patterns obtained by use of the oscillograph and a brief description of each is given.

Figure 3 is simply a line across the screen along the x-axis, and is obtained by applying the voltage of the sweep circuit to the horizontal deflection plates.

Figure 4 shows a sine wave which is obtained by applying a saw-tooth sweep to the x-axis deflection plates and a sine wave to the y-axis deflection plates. The number of cycles of the sine wave appearing on the screen is directly proportional to the frequency of the sine wave applied to the y-axis deflection plates. In order to have the sine wave appearing on the screen stationary for wave study, it is necessary to feed a low voltage from the y-axis deflection plates into the sweep circuit, so that the two voltages appearing on the x and y-axis will be harmonically related, and that the frequency of the sweep circuit will be an exact sub-multiple of that applied to the y-axis. By this method of synchronization any recurrent wave form may be held stationary on the screen.

Figure 5 shows an unmodulated radio frequency voltage applied to the y-axis deflection plates with the usual sweep circuit voltage applied to the x-axis deflection plates. The width of this band, or deflection along the y-axis, is directly proportionate to the voltage applied to the y-axis deflection plates, and is independent of the frequency of this voltage. The deflection along the y-axis varies with different cathode ray tubes from about .4 to about .6 millimeters per volt; therefore, to adjust the width of the band, it is only necessary to adjust the coupling to the radio frequency source. For accuracy in measuring percentage of modulation it is helpful to draw five horizontal lines across the screen or on a transparent scale just over the screen; for example, draw a center line such as A - A', a line above the center line such as B - B', and a third line C - C' twice the height of B - B'. For wave analysis it is well to have an opaque shield covering the entire screen below the center line, or a duplicate set of lines, identical in spacing to those above the center line, can be drawn as B" - B"', and C" - C"'. Then, if the band of radio frequency voltage is adjusted so that it extends from B - B' to B" - B"', all is in readiness for the modulating voltage to be applied.

Figure 6 is 50% modulated, for which the percentage of modulation may be calculated as follows:

$$\%\ \text{mod.} = \frac{e_{mod.} - e_{car.}}{e_{car.}} \times 100$$

If the height of the peaks above the center line is three centimeters, and the height of the unmodulated carrier is two centimeters, the following is true:

$$\frac{e_{mod.} - e_{car.}}{e_{car.}} \times 100 = \frac{3 - 2}{2} \times 100 = 50\%$$

The peaks should always be the same above the line B - B' as are the troughs below this same line, and the envelope should be symmetrical above and below this line B - B'. These statements are made under the assumption that a sine wave is applied as the modulating voltage.

Figure 7 represents the condition when the modulating voltage is increased until the radio frequency wave is completely modulated. It is observed that the peaks are touching the line C - C', and that the troughs are touching the center line A - A'. It will be observed that the wave is still symmetrical about the line B - B'. This condition is called complete or 100% modulation. By application of the above formula it is observed that:

$$100\% = \frac{e_{mod.} - e_{car.}}{e_{car.}} \times 100 = \frac{(C - C') - (B - B')}{B - B'} \times 100$$

or in other words the height of the peaks is twice the height of the carrier, or unmodulated voltage.

Figure 8 shows the all too familiar over-modulation envelope. It is observed that the peaks extend up above the line C - C', and that the troughs tend to cross the center line A - A'. Over-modulation is a serious condition which results in distortion of the modulating voltage; also the excessive power in the side bands tends to cause cross modulation with other services on near-by frequencies.

(All the above diagramsand descriptions apply to theoretical conditions, and are given as an introduction to the study of modulation.)

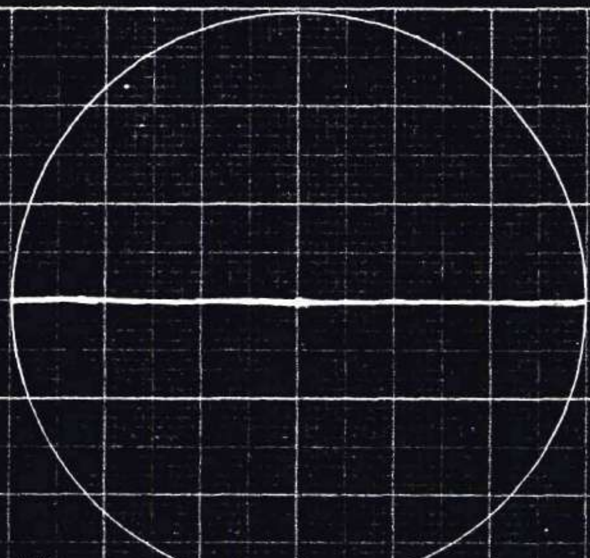


Fig 3

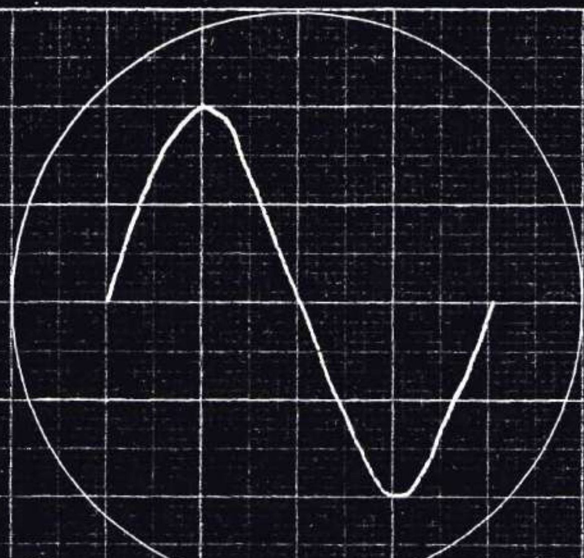


Fig 4

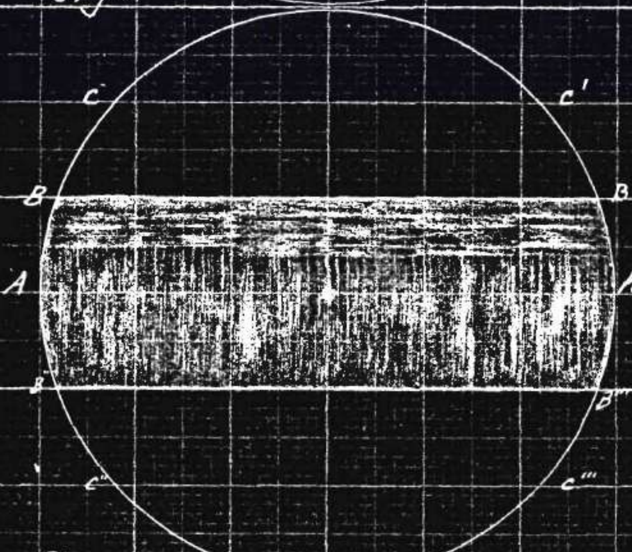


Fig 5

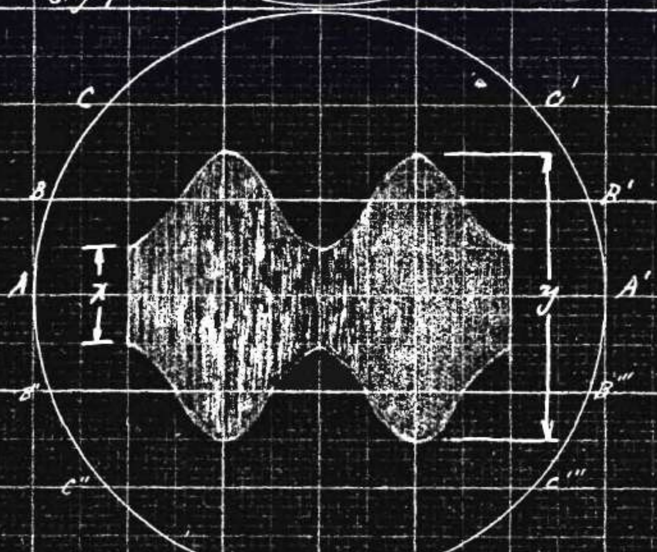


Fig 6

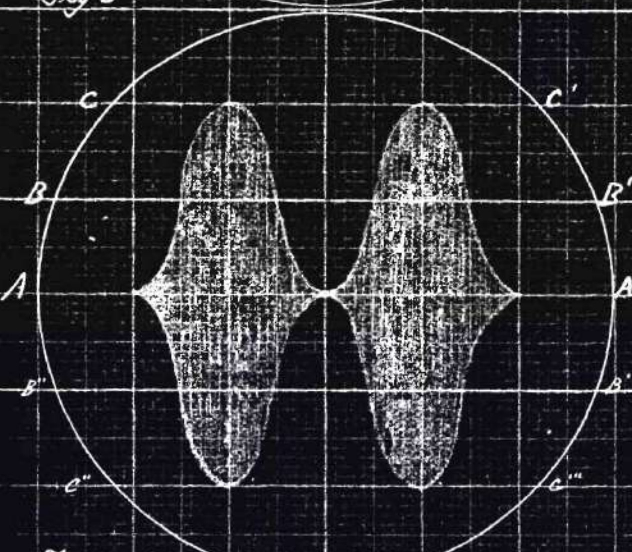


Fig 7

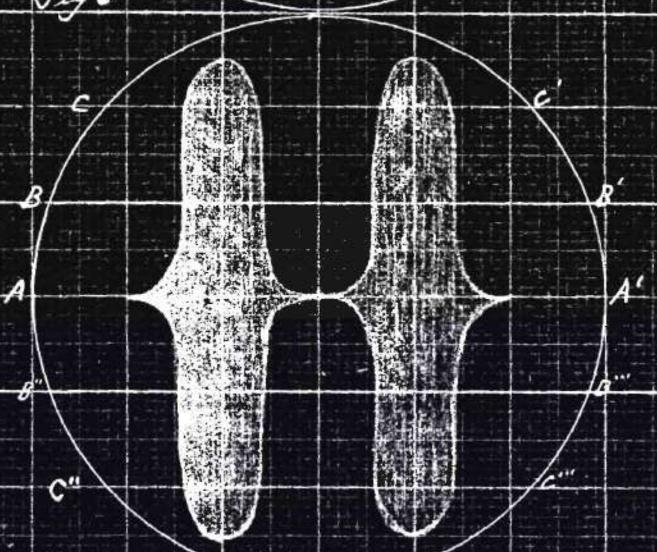


Fig 8

Patterns on an oscillograph

3/25/36 C.H. Owen

METHODS OF MODULATION

There are numerous methods, or systems, of modulation, but it is believed that fundamentally there are only three classifications; namely, modulation by means of variable circuit elements, modulation of oscillators, and modulation of amplifiers.

MODULATION BY MEANS OF VARIABLE CIRCUIT ELEMENTS was undoubtedly the earliest form of modulation, and to this day it remains one of the simplest; however, in most instances it is limited to very low power.

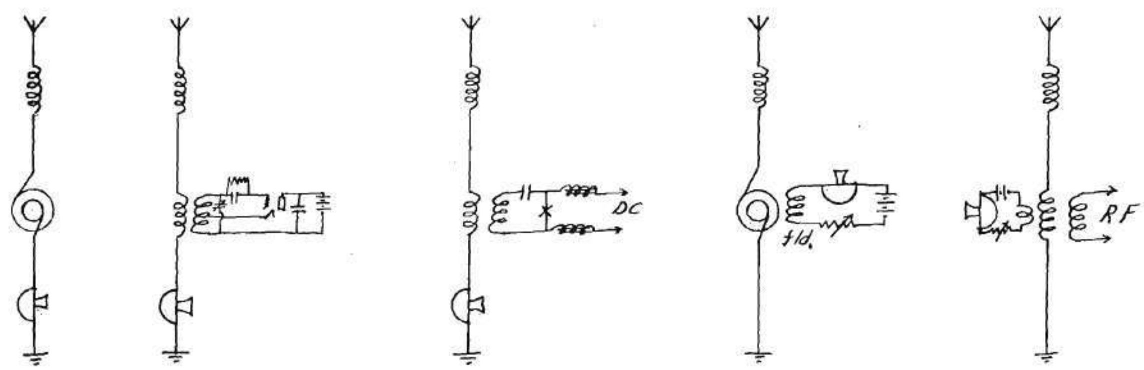


Fig. 9A   Fig. 9B   Fig. 9C   Fig. 9D   Fig. 9E

Figure 9-a shows a very simple type of telephone transmitter, while 9-b and 9-c show the high frequency generator replaced by a vacuum tube oscillator, and a high frequency arc circuit. Figure 9-d shows the most radical departure in that the variable resistance element (microphone) is not in the high frequency circuit, but in the direct current circuit supplying energy for the field excitation of the high frequency generator. Figure 9-e shows another method of modulating a high frequency wave. The

variable resistance is linked with the high frequency tuned circuit by a loop. This was known as absorption modulation, and was very popular for keying an arc transmitter. The only disadvantage was that the variable impedance of the microphone circuit was transferred to the tuned circuit so that the frequency, as well as the impedance of the tuned circuit, was varied. All of the above circuits are now considered obsolete from good engineering standpoints.

MODULATED OSCILLATORS include almost every type of modulation where there is little or no isolation between the oscillator and modulated amplifier. This isolation may be anything from separation by means of buffer amplifiers, to separation by means of shield grids as in the case of tetrodes. While the modulated oscillator is usually of the amplitude modulated type, there is nearly always some frequency drift or frequency modulation present.

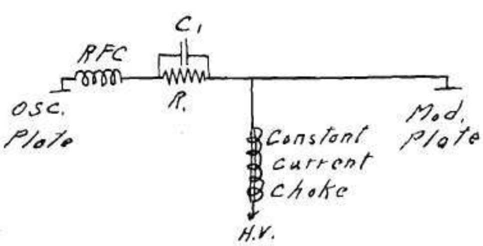


Fig. 10

Figure 10 shows a portion of an oscillator, plate modulated, (Heising system). The modulated oscillator due to its inherent tendency toward frequency modulation is practically limited to A2 emission, and for that reason is not considered of sufficient importance to warrant further discussion.

MODULATED AMPLIFIERS are almost in universal use for all types of transmitters employing A3 emission. There are three general types in common use:

Grid-bias Modulated Amplifiers

Plate Modulated Amplifiers

Suppressor-grid Modulated Amplifiers

These types of amplifiers will be discussed fully in the following chapters.

GRID-BIAS MODULATED AMPLIFIERS

Grid-bias modulated amplifiers are becoming very popular for low power transmitters. They are somewhat difficult to adjust, but this difficulty is not great enough to be objectionable. Some authors list grid-bias modulated amplifiers under the heading "Modulation by Means of Non-linear Impedances". This term is appropriate, but since the non-linear impedance in this case is an amplifier and has amplification for the radio frequency carrier, whether or not modulation voltage is applied, it is herein listed with the modulated amplifiers. Grid-bias modulation requires very little audio or modulator power for complete modulation, which is of economic value speaking in terms of modulator equipment. It has the disadvantage, however, that the plate efficiency, and hence the power output per tube, is very low; for example, for a peak carrier of 100 watts at 100% modulation the average carrier power will be only 25 watts. This means that to have an average carrier of any considerable power, the installed amplifier tube capacity must be four times this value for complete modulation. This disadvantage, stated above, is true for any amplifier amplifying a modulated wave, as is the case of the linear amplifier for low level modulation. The following figure, figure 11, shows the circuit diagram for a grid-bias modulated amplifier.

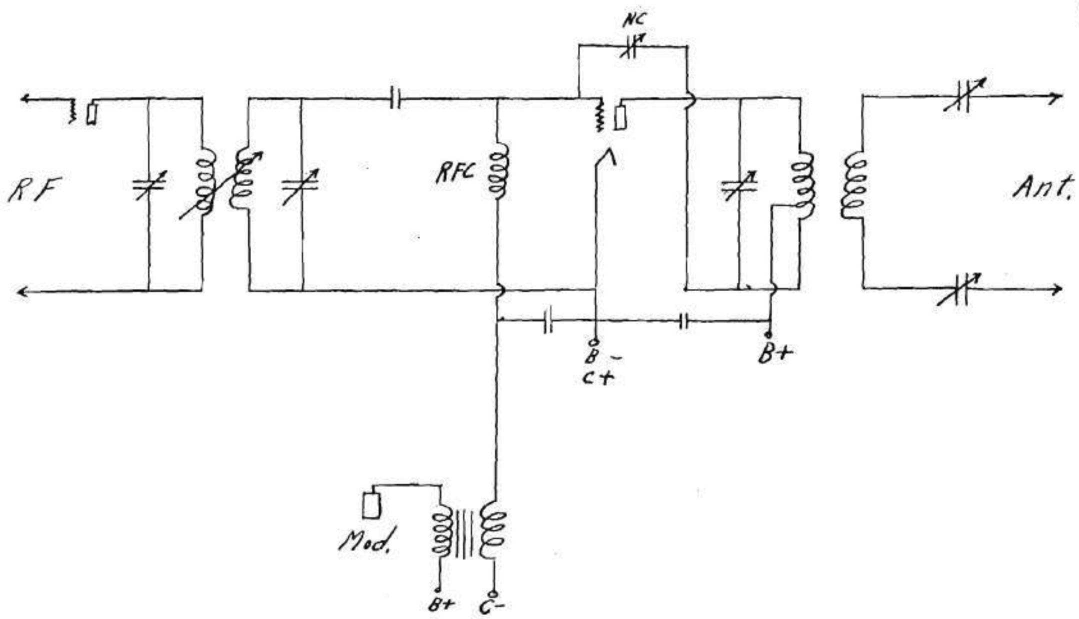


Fig. 11

The diagram shows the output of this modulated amplifier going directly to the antenna, which is usually the case. If an additional amplifier is used, this puts two linear amplifiers in series, which increases the difficulty of making and keeping correct adjustments for optimum operating conditions.

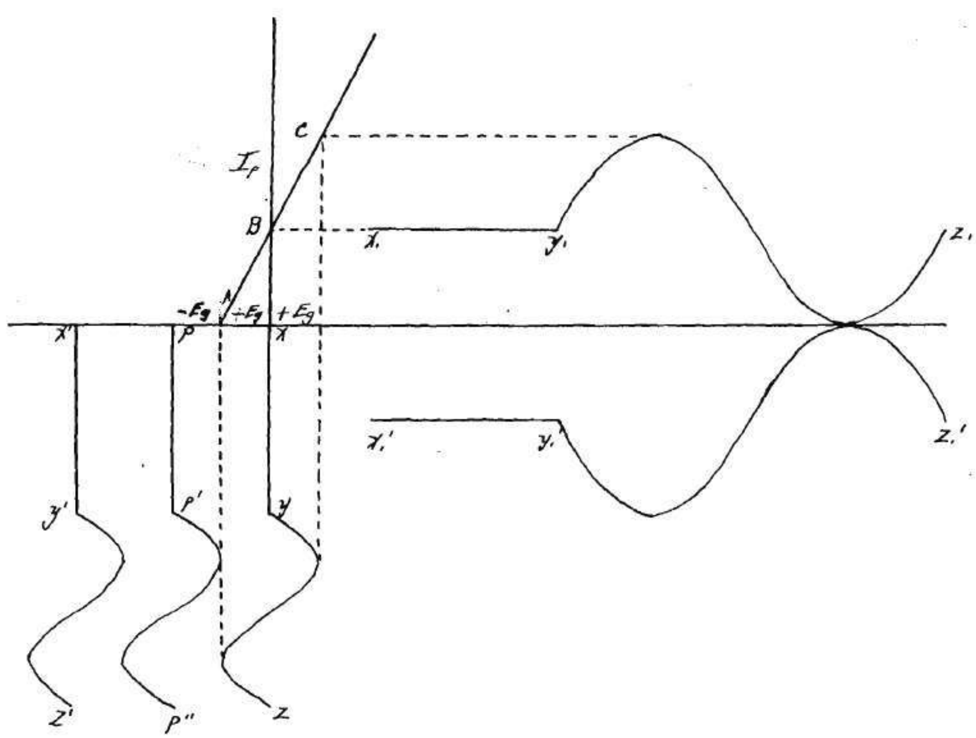


Fig. 12

Figure 12 shows graphically the operation of the grid-bias modulated amplifier. This amplifier operates as a radio frequency Class "B" amplifier, as is indicated by the linear portion A B C of the plate current-grid voltage characteristic curve. The amplifier is biased to point P in such a manner that when a sine wave of modulation voltage such as P' P" is applied to the grid, the peak of this voltage just touches the cut-off point A. The radio frequency envelope, XY X'Y', is shown altered to YZ Y'Z', as the bias voltage P' P" is varied about a fixed point P. The plate envelope X_1Y_1 $X_1'Y_1'$ corresponds to the grid envelope XY X'Y' without modulation, and Y_1Z_1 $Y_1'Z_1'$ to YZ Y'Z' with modulation. The negative portion of the plate envelope is supplied by the flywheel[2,3] effect of the plate tank circuit. It was previously stated the grid-bias modulated amplifier closely resembles the radio frequency linear amplifier. This is generally true with one major exception. With the linear amplifier the bias is fixed, and, consequently, the operating angle (that part of the cycle in which the plate current flows) is likewise fixed. In the grid-bias modulated amplifier this operating angle is constantly changing about a fixed point. To facilitate operating adjustments, the amplifier is usually biased a little beyond the cut-off point, so that it operates between positions for Class "B" and Class "C", called by W. L. Everitt Class "B'". As a summary, the grid-bias modulated amplifier is not highly efficient, and its greatest usefulness is for low power trans-

[2] Henney "Radio Engineering Handbook", Pp.320.

[3] Nilson & Hornung "Practical Radio Communications", Pp.134.

mitters. It is also used for C. W. transmitters, which have only an occasional use for telephony, and wish to economize on the modulation equipment.

PLATE CIRCUIT MODULATED AMPLIFIERS

Plate circuit modulated amplifiers are the most popular at the present time. They are almost universally operated as Class "C" amplifiers, which means that the bias is fixed at about twice the plate current cut-off value. Class "C" modulated amplifiers are generally known to be about 50% efficient, and are so rated by the Federal Communications Commission; therefore, to get 100 watts undistorted power, it will be necessary to put about 200 watts direct current power into the plate circuit; for example, if the d.c. plate voltage is 1000 volts, the steady direct current plate current would be about 200 milliamperes. There is a formula given by Prof. F. E. Terman[4] for the calculation of the undistorted power output of a modulator for driving a Class "C" amplifier:

$$P = \frac{m^2 \times P_o}{2n}$$

where m is the maximum percentage of modulation, P_o is the carrier power, n is the efficiency of the amplifier (here taken as 50%), and P is the undistorted power output of the modulator. Thus it is seen that to modulate a 100 watt carrier at 100% modulation, it requires 100 watts of undistorted audio power. It was just shown, however, that the direct current plate power input had to be 200 watts for a 100 watt carrier. From this it is seen that 300 watts of power is necessary for a carrier power of 100 watts; however, the efficiency is still 50%. The

[4] F. E. Terman "Radio Engineering", p. 371.

additional power required from the audio amplifier contributes the side band power, so that the radiated power increases from 100 watts without modulation to 150 watts with 100% modulation. (This increase in radiated power with modulation will be explained later in this treatise.) The peak voltage of the modulator should be equal to the direct current voltage of the modulated amplifier, so that the plate current and the output current varies, as the plate voltage, from zero to twice the mean value. (The power output is directly proportional to the plate power input for a Class "C" amplifier.) The Class "C" modulated amplifier draws quite a heavy current during the positive half cycles, and the plate current wave is sometimes very badly distorted, because the plate voltage is sufficient to cause saturation on the peak values. This is not detrimental, because of the "flywheel" effect of the tank circuit.

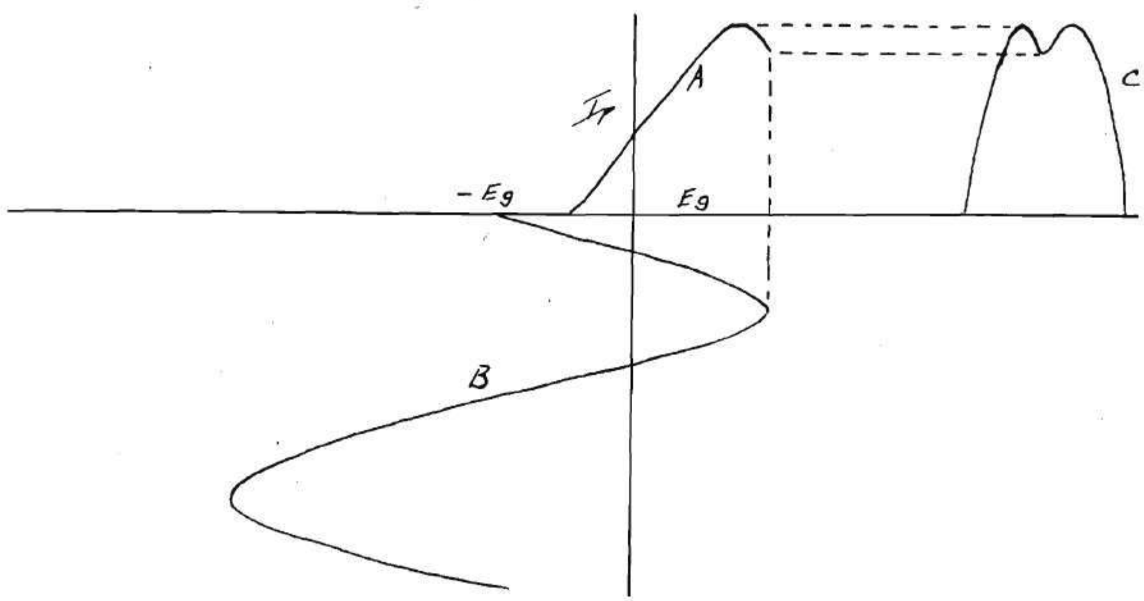


Fig. 13

Figure 13 shows the conditions for Class "C" operation where A represents the E_g - I_p curve, B the input signal, and C the plate current wave form.

Another very important factor is the value of the load impedance with respect to the plate resistance. This ratio Z_L/r should be as high as possible for linear modulation, but if it is too high some power output will be sacrificed; therefore, the above ratio should not be less than two. Furthermore, the impedance matching of the load offered to the modulator, with the rated load impedance of the modulator, deserves some careful consideration. The load offered by the modulated amplifier should be constant, and can be determined by dividing the plate voltage by the plate current. This load should be equal to the rated modulator plate load impedance.

Plate circuit modulated amplifiers are divided into two classifications (a) constant current, or Heising system of modulation, and (b) the transformer coupled type.

The constant current, or Heising system, has long been a favorite, particularly for transmitters employing modulation at low level.

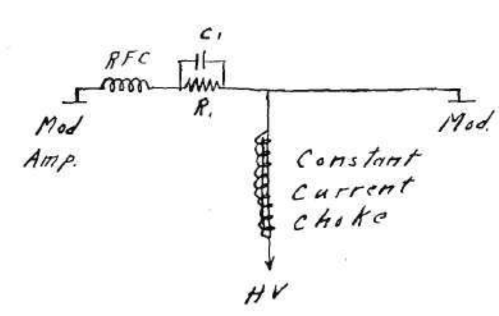


Fig. 14

Figure 14 shows a diagram of the Heising system of modulation. The plates of the modulator and modulated amplifier are connected together through the radio frequency choke coil and plate voltage dropping resistor R_1, which is shunted by a large condenser C_1. The purpose of the radio frequency choke coil is to keep the radio frequency energy from getting into the audio circuits, while the purpose of the voltage dropping resistor R_1 is to drop the plate voltage applied to the modulated amplifier to such a value that it will just be equal to the peak audio voltage from the modulator (a necessary condition for 100% modulation). Thus the same type of tubes can be used for both modulator and modulated amplifier. Quite often an auto-transformer is used in plate of the constant current choke. This makes it possible for the modulator to swing the modulated amplifier plate voltage to zero with the full plate voltage. Also there is less danger of overloading the modulator in order to obtain 100% modulation. The large shunting condenser C_1 is used in order that the maximum amount of audio voltage can be impressed upon the plate of the modulated amplifier without attenuation through R_1. The importance of having impedance offered to the modulator match its rated load impedance was previously mentioned. The most practical method of accomplishing this with the Heising system of modulation is by the proper selection of the modulated amplifier plate voltage by means of the resistance R_1.

Below is a sample calculation for determining the value of R_1. In this case a 210 type tube was used, Class "A", as modulator, with rated constants:

E_p = 425 V $\qquad P_o$ = 1.6 watts $\qquad R_p$ = 10,200 ω

Modulated amplifier plate current:

$$I_p = \sqrt{\frac{2 \times 1.6}{10,200}} = \sqrt{\frac{3.2}{10,200}} = .01775 \text{ A} = 17.75 \text{ MA}$$

Modulated amplifier plate voltage:

$$E_p = \frac{2 \times 1.6}{.01775} = 180.4 \text{ V}$$

Two times the power is used in the above formulas, because it is necessary that the direct current power to the modulated amplifier equal the peak undistorted power output of the modulator.

$$\therefore \quad 425 - 180.4 = 244.6 \text{ volts drop in resistor } R_1$$

$$R_1 = \frac{244.6}{.01775} = 13,800\ \omega \quad \text{value of } R_1$$

The capacity of R_1 should be:

$$13,800 \times (0.01775)^2 = 4.3 \text{ watts, or 5 watts}$$

From the above calculations it can be seen that the load offered to the modulator is 180.4/.01775 = 10,200 ω which is the rated load impedance for the modulator tube. The ohmic resistance of the radio frequency choke should be as low as possible. The value of the constant current choke cannot be determined quite so readily, but it is sufficient to say that it should be large enough that the direct current load on the power supply does not change when modulation is applied. This condition can very easily be determined by placing a milliameter of sufficient capacity in the high voltage lead between the power supply and the constant current choke.

The transformer coupled system of plate modulation is usually used with a Class "B" modulator, and for that reason will be explained from the standpoint of Class "B" operation. The modulated amplifier is of the Class "C" type, as was used with the Heising system of modulation.

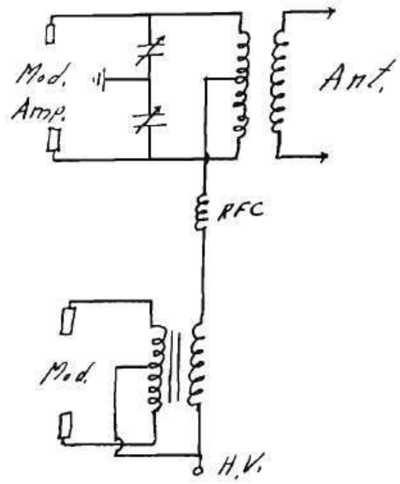


Fig. 15

Figure 15 shows a typical circuit used with the transformer coupled system of modulation. This diagram shows a balanced modulated amplifier used with a Class "B" modulator. This combination is quite often used, as all four tubes are of the same type and have the same plate voltage applied to their plates. With the Class "B" modulator, operating at audio frequency, it is necessary to use two tubes in push-pull for the reason the tubes are biased to cut-off, and consequently each one passes only one-half of the cycle. By putting two of them in push-pull, each one passes one-half of the cycle, or together they pass the entire cycle. This is shown graphically by Figure 16.

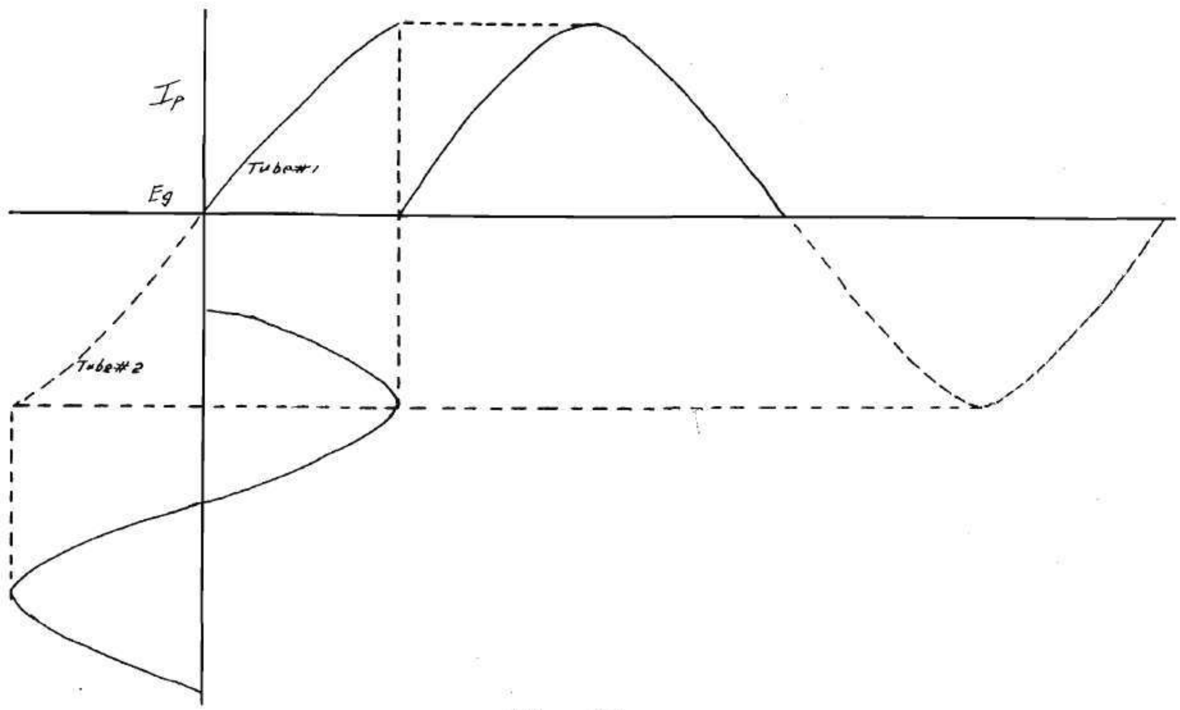


Fig 16

The main advantage of Class "B" operation is that with two tubes operating push-pull, the undistorted output is exceedingly high, while the plate current is comparatively low, because only one tube is drawing plate current at a time, and then only in proportion to the signal input. The Class "B" audio amplifier, or modulator, will give practically distortionless outputs of great volume, and do it economically in so far as plate current is concerned, and also as far as filament current is concerned there is no practical reason why all Class "B" audio amplifier tubes could not be built with both tubes in the same envelope, using the same filament, as only one plate is attracting electrons at any one time. The transformer coupled system of modulation does not have a current limiting device such as the Heising choke, but depends upon the induction of the transformer to swing the modulated amplifier's plate voltage to zero for 100% modulation. Obviously this Class "B" modulation transformer is the very heart of this system of modulation. Not only must it have the proper turns ratio for correctly matching the impedances, but the tapped primary must be perfectly balanced or either the positive or negative peaks will be distorted. It must also be capable of handling considerable power, but must do so without giving rise to distortion within the transformer itself. Below are given some sample calculations for determining the proper turns ratio of the modulation transformer. Assuming that type 10 tubes are used with balanced modulated amplifier and Class "B" modulator, the necessary Class "B" operating data are:

$E_p = 600$ V. $I_p = 153$ MA. $R_L = 8000\,\omega$. $P_1 = 57.5$ W.(output)

Again it is mentioned that the modulator power output is only about one-half of the (DC)power input to the modulated amplifier

Plate current (modulated amplifier):

$$I_{p_1} = \frac{2 \times P_1}{E_p} = \frac{2 \times 57.5}{600} = .192 \text{ A}$$

Modulating impedance (offered by modulated amplifier to the transformer):

$$Z_m = \frac{E_p}{I_{p_1}} = \frac{600}{.192} = 3130\,\omega .$$

The rated impedance of two type 10 tubes operating Class "B" is 8000 ω. The transformer will, therefore, have to have the proper turns ratio for matching these two impedances. The turns ratio will be the square root of the impedance ratio, or

$$\text{turns ratio} = \sqrt{\frac{8000}{3130}} = 1.6 \text{ to } 1.$$

That is, a step-down transformer is required with 1.6 times as many primary as secondary turns. The primary will have to be tapped at its exact electrical center, and the transformer will have to be of sufficient size so as to handle the 57.5 watts with reasonable efficiency. As a summary, the plate system of modulation is **advantageous** for several reasons; it is highly efficient, particularly when used with a Class "B" modulator; it can be used for high percentage of modulation with low distortion; and adjustments are relatively few and simple.

SUPPRESSOR-GRID MODULATED AMPLIFIERS

Suppressor-grid modulation is without a doubt the newest and simplest of them all. It is a compromise between the grid-bias modulation and plate modulation. In some respects it resembles the grid-bias type in that with a completely modulated wave the rated carrier power is only about one-fourth the plate input power; however, more audio power is required for complete modulation than is the case for the grid-bias system because the location of the suppressor-grid is farther from the cathode than the control grid.

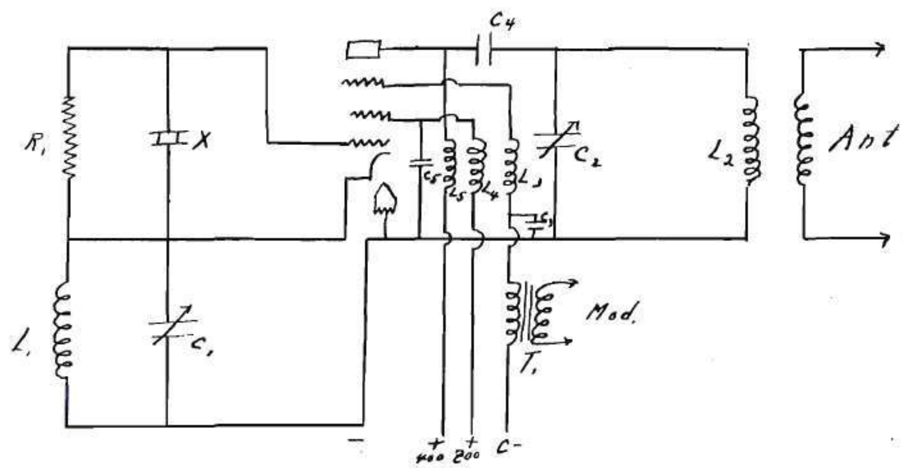


Fig. 17

Figure 17 shows a diagram of the suppressor-grid system of modulation. This diagram shows a "tri-tet" oscillator with suppressor-grid modulation. As this circuit was used in most of the experiments in obtaining data for this thesis, it will be explained somewhat in detail. The tube used was a type 59, which functioned as a crystal control oscillator, buffer amplifier, and modulated amplifier. This tube was chosen in preference to the RK 20 type of tube, because all the information regarding suppressor-grid modulation could be obtained with it, and the power output was not of importance. The circuit consists of four fundamental divisions, which are classified as follows: the crystal oscillator grid circuit is represented by R_1 and X, R_1 being the grid leak; the resonant circuit, which normally would be the plate circuit of a triode oscillator, is represented by L_1 and C_1; the power amplifier tank circuit is represented by L_2 and C_2; and T_1, together with the suppressor, is the modulation circuit.

Figure 18 shows the dynamic characteristic curve of the plate voltage versus plate current. It is noted that this curve is very similar to the $I_p - E_p$ characteristic curve for the triode in that it is practically straight except at the extreme lower end where it approaches zero.

In Figure 19 the suppressor-grid voltage vs. plate current curve is practically straight over the greater part of the curve; its similarity to the suppressor-grid voltage versus radio frequency tank current curve, as shown in Figure 20, should be noted. It should also be noted that the curves cross the axis of zero bias near the top. One very important item in consideration of the similarity of the two curves is the proper point to set the suppressor-grid bias. Obviously it is desirable to set the bias near the middle of the straight portion of the curve. It is noted from observation of the two curves that the middle of the straight portion is approximately forty-five volts (negative). Some authors arrive at the same point of proper suppressor-grid bias by applying positive bias until the maximum amount of antenna current is obtained, and then applying negative bias until exactly half this amount of antenna current is indicated. The operating point must be placed in the middle of the straight portion of the characteristic curve if maximum percentage of modulation is to be obtained with little distortion. From observation of the curve of Figure 20, however, it is seen that it is not desirable to try to obtain complete, or 100% modulation, as that would mean drivingthe plate current to absolute zero, and it can be seen that the lower portion of the curve departs considerably from a straight line. It goes without saying that to have a distortionless modulation the curve should be perfectly straight to the zero axis. It is also interesting to note that from curve of Figure 20, the maximum percentage of modulation with reasonably little distortion can be calculated. As was previously stated, the proper bias should be about (negative) forty-five volts. The curve reaches a peak of 322 milliamperes without greatly departing from a straight line. This peak occurs at a positive voltage of fifty volts, which makes the suppressor-grid swing in the positive direction the algebraic difference between these two voltages, or ninety-five volts. The swing in the negative direction would be the same amount, or from negative forty-five to negative one hundred forty volts; therefore, the total grid swing is from positive fifty volts to negative one hundred forty volts, or a total of one hundred ninety volts. The radio frequency tank currents corresponding to these suppressor-grid voltages are taken from the curve and are:

$$50 \text{ V} = 322 \text{ MA}$$

$$-45 \text{ V} = 155 \text{ MA}$$

$$-140 \text{ V} = 19.5 \text{ MA}$$

It can be assumed that the radio frequency voltage across the condenser is proportional to the current. We can now calculate percentage modulation by applying the formula previously cited:

$$\frac{E_{mod.} - E_{car.}}{E_{car.}} \times 100 = \% \text{ mod.}$$

For the purpose at hand this formula will be changed to the following:

On positive peak, $\quad \% \text{ mod.} = \dfrac{I_{max.} - I_{ave.}}{I_{ave.}} \times 100$

On negative peak, $\quad \% \text{ mod.} = \dfrac{I_{ave.} - I_{min.}}{I_{ave.}} \times 100$

Average mod. on positive and negative peaks,

$$= \frac{I_{max.} - I_{min.}}{2\ I_{ave.}} \times 100$$

Substituting numerical values:

$$m = \frac{322 - 19.5}{2(155)} \times 100 = 97.5\%$$

This degree of modulation is not without some distortion, but it is about the highest percentage of modulation that can be had with limited distortion. It was previously mentioned that less modulator voltage was required for suppressor-grid modulation than for plate modulation. This can be shown mathematically by reference to curves of Figures 20 and 21. First, referring to the curve of Figure 20, it is observed that to change radio frequency tank current from 100 MA to 200 MA it requires (-77) - (-20), or 57 volts change, as applied to the suppressor-grid. Secondly, by observation of the curve of Figure 21, it is noted that to change from 100 MA to 200 MA, it requires 402 - 228, or 174 volts, as applied to the plate. It can be said that the amplification factor of the tube from suppressor-grid to plate is 174/57, or 3.055; or another way of stating the same thing is that only 32.2% of the modulator voltage is required for suppressor-grid modulation as compared to plate modulation.

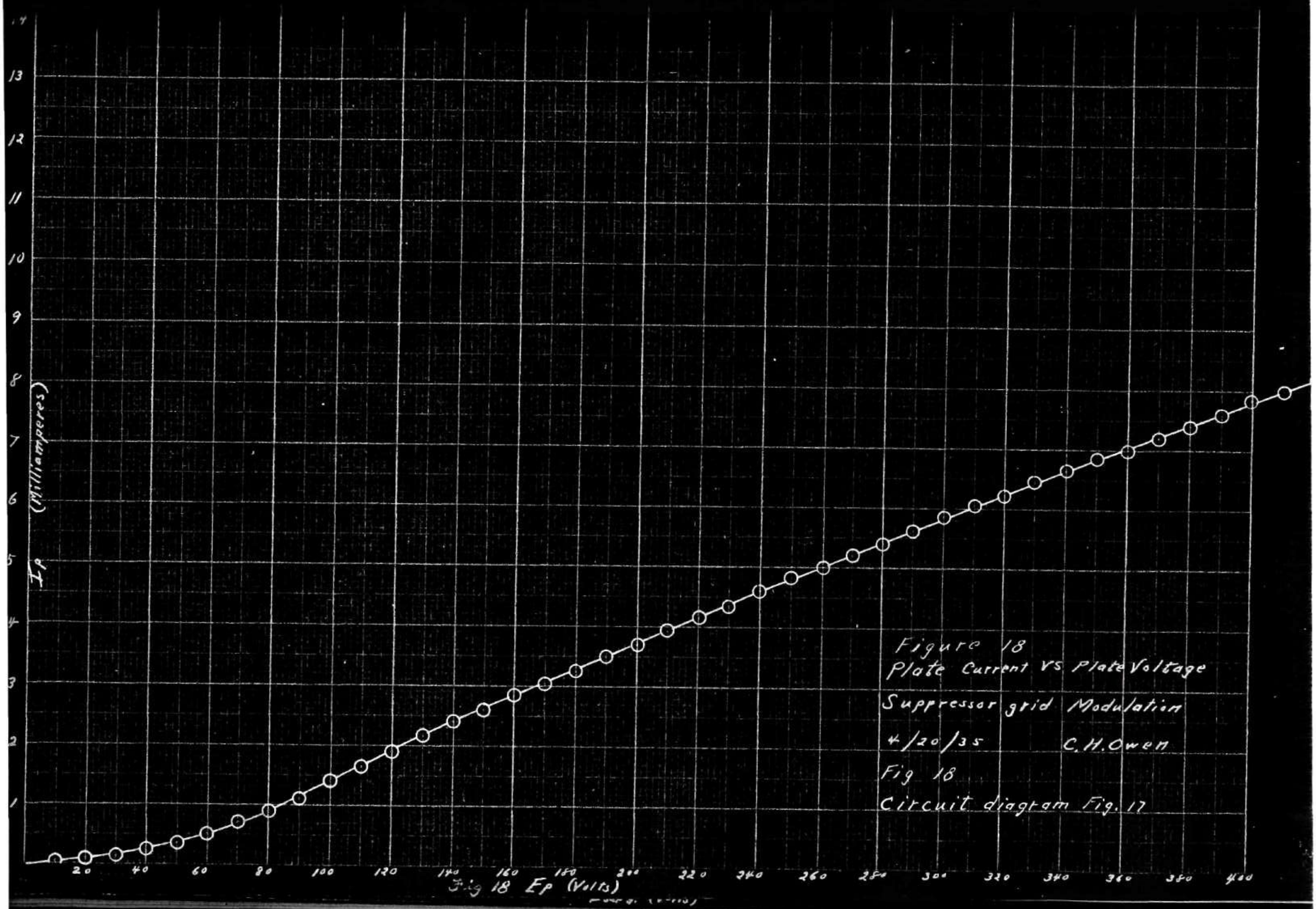


Figure 18
Plate Current vs Plate Voltage
Suppressor grid Modulation
4/20/35 C.H.Owen
Fig 18
Circuit diagram Fig. 17
Ip (Milliamperes)
Fig 18 Ep (Volts)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400

Data for Figure 18.

$E_{sup\ g} = -42$

$E_{sg} = +78$

E_p	I_p	E_p	I_p
V	MA	V	MA
435	8.4	210	3.92
430	8.35	200	3.7
420	8.2	190	3.5
410	8.0	180	3.25
400	7.85	170	3.02
390	7.6	160	2.85
380	7.4	150	2.6
370	7.2	140	2.4
360	7.0	130	2.17
350	6.85	120	1.9
340	6.65	110	1.65
330	6.45	100	1.4
320	6.22	90	1.1
310	6.1	80	.9
300	5.85	70	.7
290	5.62	60	.5
280	5.4	50	.35
270	5.2	40	.22
260	5.0	30	.12
250	4.82	20	.082
240	4.6	10	.037
230	4.35	5	.015
220	4.15		

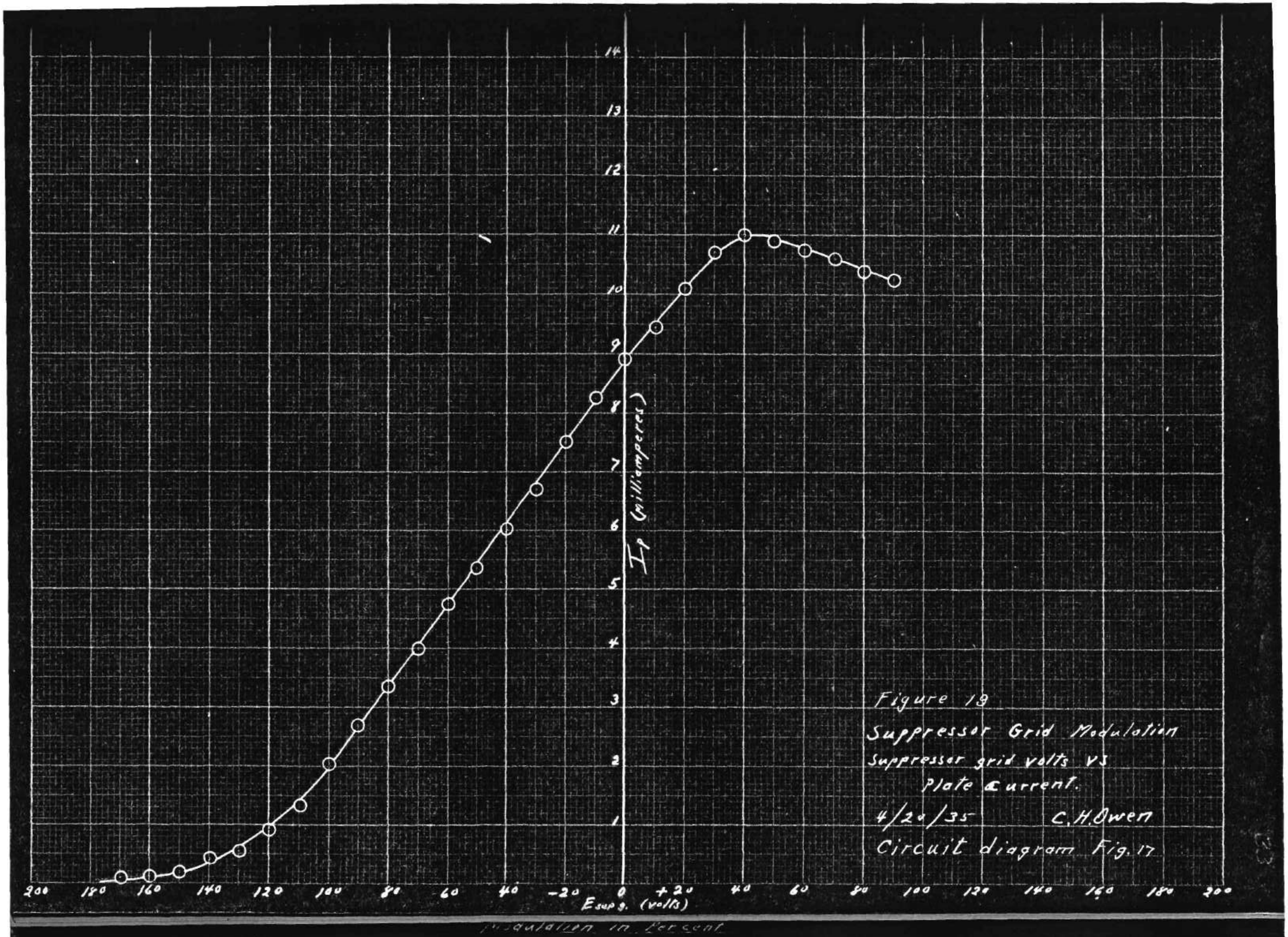


Figure 19
Suppressor Grid Modulation
Suppressor grid volts VS
Plate Current.
4/20/35 C.H.Owen
Circuit diagram Fig. 17

Data for Figure 19.

E_p = 300 V $\qquad$ E_{sg} = 78 V

$E_{sup\ g}$ V	I_p MA	$E_{sup\ g}$ V	I_p MA	$E_{sup\ g}$ V	I_p MA
0	8.9	-5	8.6	− 100	2.05
+ 5	9.2	10	8.25	105	1.7
10	9.45	15	7.8	110	1.35
15	9.8	20	7.5	115	1.12
20	10.1	25	7.15	120	.95
25	10.45	30	6.7	125	.74
30	10.7	35	6.4	130	.55
35	10.9	40	6.05	140	.45
40	11.0	45	5.7	145	.25
45	11.0	50	5.38	150	.20
50	10.9	55	5.05	155	.155
55	10.8	60	4.75	160	.13
60	10.75	65	4.35	165	.11
65	10.7	70	4.0	170	.10
70	10.6	75	3.65	175	.09
75	10.5	80	3.35	180	.085
80	10.4	85	3.0		
85	10.3	90	2.7		
90	10.25	95	2.4		

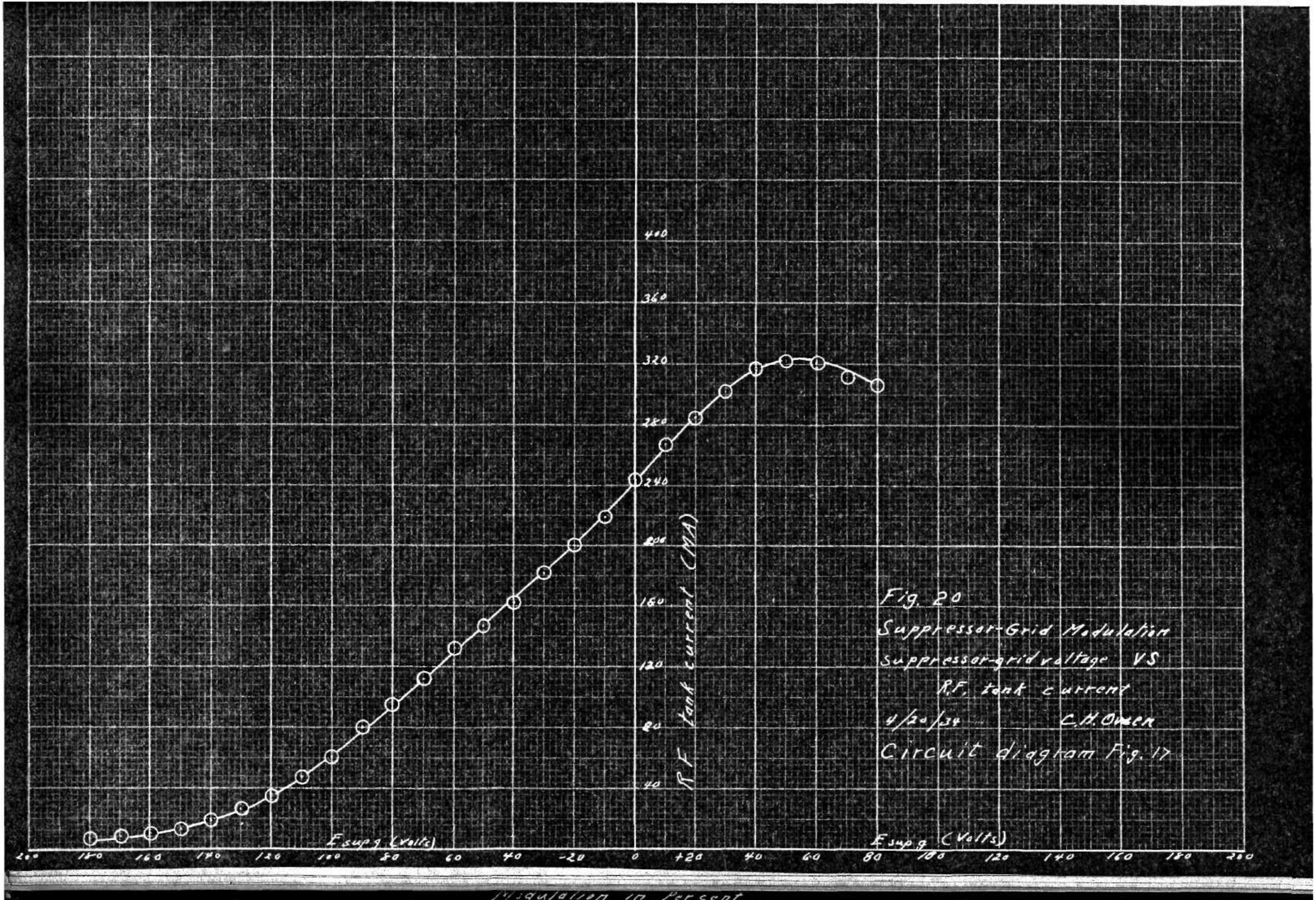


Fig. 20
Suppressor-Grid Modulation
suppressor-grid voltage VS
R.F. tank current
4/20/34 C.H. Owen
Circuit diagram Fig. 17
R.F. tank current (MA)
400
360
320
280
240
200
160
120
80
40
Esup g (volts)
Esup g (Volts)
200
180
160
140
120
100
80
60
40
-20
0
+20
40
60
80
100
120
140
160
180
200
Modulation in Percent

Data for Figure 20.

E_{sg} = 80 V E_p = 300 V

$E_{sup\ g}$ V	TC* #63	I_{tank} MA
+ 80	1.73	307
70	1.79	311
60	1.9	320
50	1.93	322
40	1.84	317.5
30	1.67	302
20	1.49	285
10	1.305	267
0	1.11	244
-10	.91	219
20	.76	200
30	.635	182.5
40	.50	162.5
50	.41	147
60	.33	132
70	.238	112
80	.17	95
90	.115	80

$E_{sup\ g}$ V	TC* #84	I_{tank} MA
− 90	1.83	78
100	1.16	61
110	.715	48
120	.41	35.8
130	.22	26.5
140	.11	19.5
150	.05	13.2
160	.03	11
170	.016	8.5
180	.010	7.5

*Thermocouple.

Note: Nos. 63 and 84 are reference numbers of the thermocouples used in this experiment.

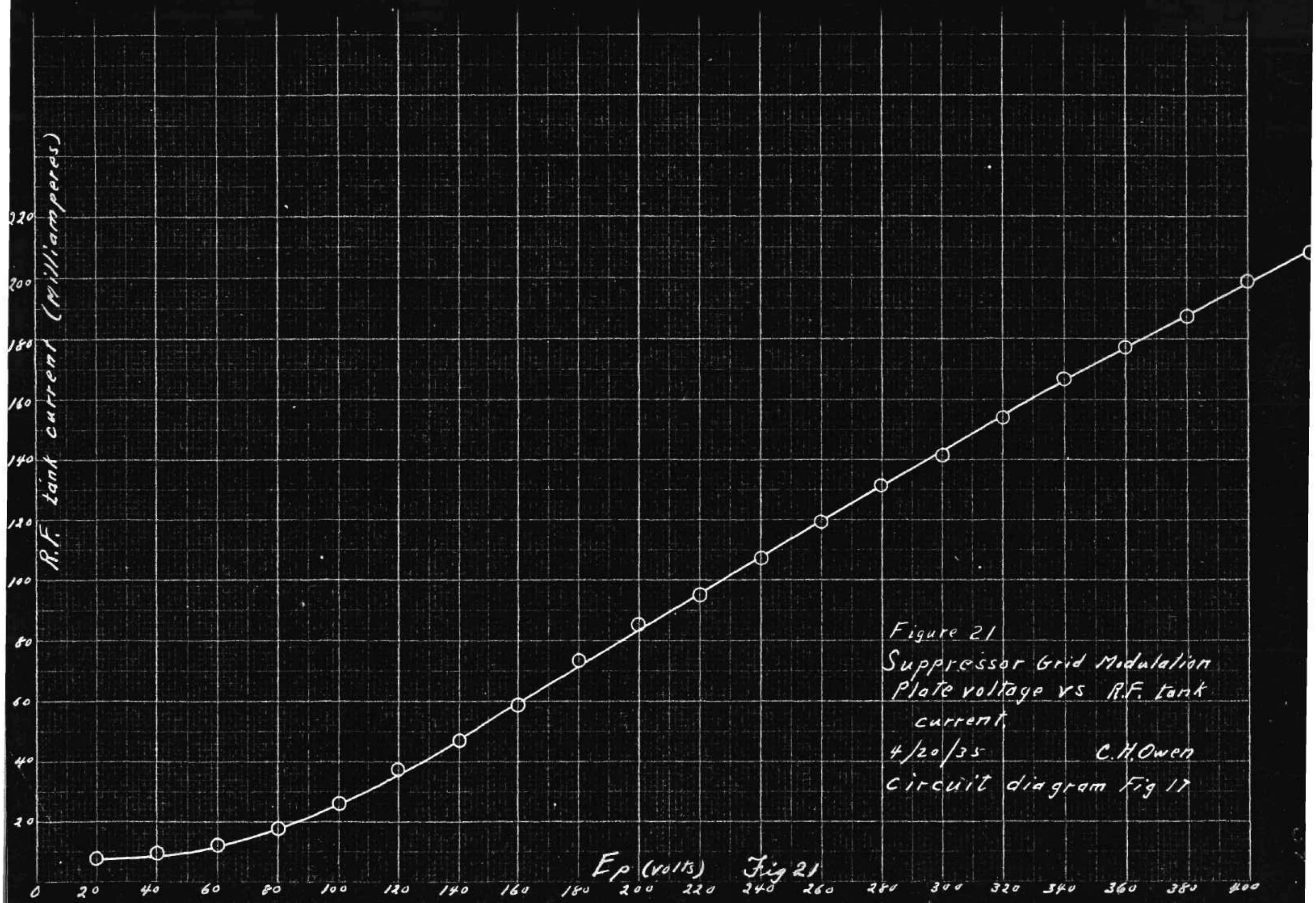


Figure 21
Suppressor Grid Modulation
Plate voltage vs R.F. tank current.
4/20/35 C.H. Owen
Circuit diagram Fig 17
R.F. tank current (milliamperes)
Ep (volts)
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 380 400
20 40 60 80 100 120 140 160 180 200 220
Fig 21

Data for Figure 21.

$E_{sup\ g}$ = - 45 V E_{sg} = +80 V

E_p V	TC*	RF I_{tank} MA
	#63	
420	.83	208
400	.755	199
380	.67	187.5
360	.59	177
340	.525	167
320	.45	154
300	.38	141
280	.328	131
260	.27	119
240	.215	107
220	.17	95
200	.13	85
180	.095	73
	#84	
180	1.525	70.6
160	1.07	58.5
140	.695	47
120	.425	37.6
100	.21	26
80	.09	17.2
60	.04	12
40	.02	9.5
20	.01	7.5

*Thermocouple.
Note: Nos. 63 and 84 are reference numbers of the thermocouples used in this experiment.

THE EFFECT OF MODULATION IN INCREASING THE CURRENT OR POWER IN THE VARIOUS CIRCUITS

It is interesting to observe the changes in the various circuits as the result of modulation. An example of one of these changes is the power increase. If the assumption is made that two alternating current voltages are used to modulate a direct current voltage, then a mathematical explanation of the power increase can be made by Taylor's series.

Let:

$$E = E_o + E_1 \sin \omega t + E_2 \sin \rho t$$

where E is the resultant or vectorial voltage,

E_o is the direct current voltage,

E_1 is the radio frequency voltage (f = 1000 kilocycles),

E_2 is the audio frequency voltage (f = 1000 cycles).

Also, as the modulator is a nonlinear device, for closer approximation there should be added a parabolic or squared term as follows:

$$I = I_o + C_1 (E - E_o) + C_2 (E - E_o)^2$$

Now substitute for E in the above equation the value of E previously given and obtain:

$$I = I_o + C_1 (E_o + E_1 \sin \omega t + E_2 \sin \rho t - E_o) + C_2 (E_o + E_1 \sin \omega t + E_2 \sin \rho t - E_o)^2$$

Expanding:

$$I = I_o + C_1 (E_1 \sin \omega t + E_2 \sin \rho t) + C_2 (E_1^2 \sin^2 \omega t + 2E_1 E_2 \sin \omega t \sin \rho t + E_2^2 \sin^2 \rho t)$$

By trigonometry:

$$\sin^2\theta = \frac{1-\cos 2\theta}{2}$$

$$\therefore \sin^2\omega t = \frac{1-\cos 2\omega t}{2}$$

$$\& \quad \sin^2\rho t = \frac{1-\cos 2\rho t}{2}$$

Substitute these values in the equation for I and obtain:

$$I = I_o + C_1\,(E_1\sin\omega t + E_2\sin\rho t) + C_2\left[E_1^2\left(\frac{1-\cos 2\omega t}{2}\right) + 2E_1E_2\sin\omega t\sin\rho t + E_2^2\left(\frac{1-\cos 2\rho t}{2}\right)\right]$$

$$= I_o + C_1\,(E_1\sin\omega t + E_2\sin\rho t) + C_2\left[\frac{E_1^2}{2} - \frac{E_1^2}{2}\cos 2\omega t + 2E_1E_2\sin\omega t\sin\rho t + \frac{E_2^2}{2} - \frac{E_2^2}{2}\cos 2\rho t\right]$$

Also by trigonometry:

$$\cos(\omega-\rho)t = \cos\omega t\cos\rho t + \sin\omega t\sin\rho t$$

$$\& \quad \cos(\omega+\rho)t = \cos\omega t\cos\rho t - \sin\omega t\sin\rho t$$

Subtract and obtain:

$$\cos(\omega-\rho)t - \cos(\omega+\rho)t = 2\sin\omega t\sin\rho t$$

$$\text{or} \quad \frac{\cos(\omega-\rho)t - \cos(\omega+\rho)t}{2} = \sin\omega t\sin\rho t$$

$$\therefore I = I_o + C_1\,(E_1\sin\omega t + E_2\sin\rho t) + C_2\left[\frac{E_1^2}{2} - \frac{E_1^2}{2}\cos 2\omega t + 2E_1E_2\left(\frac{\cos(\omega-\rho)t - \cos(\omega+\rho)t}{2}\right) + \frac{E_2^2}{2} - \frac{E_2^2}{2}\cos 2\rho t\right]$$

$$I = I_o + C_1 \ (E_1 \sin \omega t + E_2 \sin \rho t) +$$
$$\frac{C_2}{2} \left[E_1{}^2 - E_1{}^2 \cos 2 \omega t + 2E_1E_2 \cos (\omega - \rho)t - \right.$$
$$\left. 2E_1E_2 \cos (\omega + \rho)t + E_2{}^2 - E_2{}^2 \cos 2 \rho t \right]$$

I_o can be neglected as it is a direct current component. Also the double frequency terms involving 2ω and 2ρ can be neglected as far as this discussion is concerned.

Then

$$I = C_1 \ (E_1 \sin \omega t \quad E_2 \sin \rho t) +$$
$$\frac{C_2}{2} \left[E_1{}^2 + 2E_1E_2 \cos (\omega - \rho)t - \right.$$
$$\left. 2E_1E_2 \cos (\omega + \rho)t \quad E_2{}^2 \right]$$

It is noticed there are two direct current terms which have appeared and can also be neglected.

Therefore:

$$I = C_1 \ (E_1 \sin \omega t + E_2 \sin \rho t)$$
$$\frac{C_2}{2} \left[2E_1E_2 \cos (\omega - \rho)t - 2E_1E_2 \cos (\omega + \rho)t \right]$$
$$= C_1 \ (E_1 \sin \omega t + E_2 \sin \rho t) +$$
$$C_2E_1E_2 \left[\cos (\omega - \rho)t - \cos (\omega + \rho)t \right]$$

Assume $\frac{\omega}{2\pi} = $ 1,000,000 cycles

and $\frac{\rho}{2\pi} = $ 1,000 cycles

The tuned circuits will eliminate all frequencies except $\frac{\omega}{2\pi}$, $\frac{\omega - \rho}{2\pi}$, and $\frac{\omega + \rho}{2\pi}$, or 1,000,000, 990,000, and 1,001,000 cycles.

Then the expression will become:

$$I = C_1E_1 \sin\omega t + C_2E_1E_2 \left[\cos(\omega - \rho)t - \cos(\omega + \rho)t\right]$$

Now substituting back:

$$\cos(\omega - \rho)t - \cos(\omega + \rho)t = 2 \sin\omega t \sin\rho t$$

$$I = C_1E_1 \sin\omega t + 2C_2E_1E_2 (\sin\omega t \sin\rho t)$$

$$= C_1E_1 \sin\omega t \left(1 + \frac{2C_2E_2}{C_1} \sin\rho t\right)$$

The term $\frac{2C_2E_2}{C_1}$ is a constant called the modulation factor.

$$\therefore I = C_1E_1 \sin\omega t (1 + m \sin\rho t)$$

Now if m is equal to unity, or 100% modulation, then

$$I = C_1E_1 \sin\omega t (1 + \sin\rho t)$$

And if the instant were taken when both $\sin\omega t$ and $\sin\rho t$ are maximum, the peak current would be:

$$I = C_1E_1 \times 1 (1 + 1)$$

$$= C_1E_1 \times 2$$

$$= 2C_1E_1$$

Therefore, the instantaneous peak current would be twice the value of the unmodulated peak current. In a similar manner it can be shown the instantaneous peak voltage would be twice the unmodulated peak voltage, and it is also quite evident that the instantaneous peak power is four times as great as the unmodulated carrier power.

The carrier and the two side bands represent three different frequency components. The carrier may be assumed to have an effective value of one and each of the side bands

Modulation in Percent

an effective value of one-half. The square root of the sum of the squares of these effective current (or voltage) values would be:

$$
\begin{aligned}
I &= \sqrt{1^2 + .5^2 + .5^2} \\
&= \sqrt{1 + .25 + .25} \\
&= \sqrt{1.5} \\
&= 1.225
\end{aligned}
$$

The power varies directly as the square of the effective current; therefore

$$
\begin{aligned}
P &= I^2 R \\
&= 1.225^2\ R \\
&= 1.5\ R
\end{aligned}
$$

So the effective power in a 100% modulated wave is 1.5 times the power of an unmodulated wave, and the instantaneous peak power in a 100% modulated wave is four times the average power of an unmodulated wave.

It was stated previously that the frequencies desirable for transmission were 1,000,000, 990,000, and 1,001,000 cycles. Of these, the first is the original radio frequency introduced (known as the carrier), the power for which is supplied by the direct current input to the plate of the modulated amplifier. The other two frequencies are known as side bands, and are the intelligence bearing portion of the signal. These side band frequencies are equal to $\frac{\omega \pm p}{2\pi}$, and are equi-distant from the carrier. The power in the side bands is supplied by the modulator in plate modulated amplifiers, while in both grid and suppressor grid modulated amplifiers the total radiated power is supplied by *the direct current input to the modulated amplifier.* For all types of grid modulated amplifiers it is necessary to have about four times the installed tube capacity for 100% modulation as that required for the carrier alone; therefore, it is necessary to have a much larger installed tube capacity for linear and grid modulated amplifiers than for high level plate modulated amplifiers.

It is a well known fact that the antenna current increases about 22.5% when the percentage of modulation is changed from zero to 100%. The reason for this is that for a completely modulated wave the power in the side bands is 50% of that in the carrier, namely, 25% in the upper side band and 25% in the lower side band, and the total power radiated is 150% of that in the carrier with no modulation. The antenna power equals I^2R, therefore, the increase in current alone would be the square root of 1.5, or 1.225, which gives a difference of 22.5% due to modulation. This is also expressed by the formula:

$$m = \sqrt{2\left(\frac{I_m^2}{I^2} - 1\right)}$$

where m = percentage of modulation,

I_M = antenna current with modulation,

I = antenna current without modulation.

Another way of writing this same expression is:

$$I_M = \sqrt{I\left(\frac{m^2}{2} + 1\right)}$$

Figure 22 shows a curve with percentage of modulation plotted against antenna current increase in percent. As is indicated in this figure, the smooth curve indicates the mathematical values, while the circles indicate the experimental values obtained. The cathode ray oscillograph was used to determine the percentage of modulation. This method is fairly accurate for the higher percentages of modulation.

It was stated above that the radiated power, or the power in the antenna, increased from 100% to 150% when the percentage of modulation was increased from zero to 100%. The mathematical expression for this is:

$$P_M = \frac{2 + m^2}{2} \times 100$$

where P_M = percentage of radiated power,

m = percentage of modulation.

Figure 23 shows the relation for the various percentages of modulation as plotted against percentage of radiated power. For a transmitter rated at 100 watts with 100% modulation, the actual radiated power is 150 watts. It is very important for a broadcast station to have as high a percentage of modulation as possible, but not too high if distortion is to be avoided. For high fidelity there must be little or no distortion. The reason for having as high a percentage of modulation as possible is twofold; first, is the actual increase in radiated energy, which means a greater primary coverage area; and, second, of even greater importance, is the fact that the actual intelligence is carried by the side bands. This increase in power radiated by the side bands is shown in Figure 24, with the radiated power in the side bands calculated as the percentage of the total radiated power. For 100% modulation the power in the side bands is one-third of the total radiated power.

Figure 25 shows the detector plate current increase in percentage versus percentage of modulation. The mathematical formula for this is:

$$I_M - I = \Delta I = \frac{m^2}{2} \times 100$$

where I_M is plate current with modulation,

I is plate current without modulation,

m is percent of modulation.

As will be noted from the curve, the detector plate current increase for 100% modulation is 50%, or the plate current when the modulation is 100% is 150% of that with no modulation. It is observed that this curve is identical with that of Figure 23, except that the curve of Figure 23 was plotted for 100% plus the values. It can be stated that the detector plate current is directly proportional to the power radiated, from which it is evident that the detector used was a plate circuit detector. The detector used to establish these facts was a type 30 tube with cathode resistance for self bias.

The study of audio power requirements for modulation is shown in Figures 26 and 27. A General Radio volume indicator, which uses six milliwatts as zero level, was used. Figures 26 and 27 show the audio power in decibels as ordinates against percentage of modulation as abscissas. The curve of Figure 26 is plotted on semi-logrithmic paper. It is noted that in general the points follow a straight line. The probable reason why more of the points did not lie on the curve was the difficulty of accurately determining the percentage of modulation. The absolute accuracy of determining the percentage of modulation with an oscillograph is only about 10%, and this accuracy is only true of the higher percentages of modulation. It is noted from Figure 26 that at zero level the percentage of modulation is about four percent.

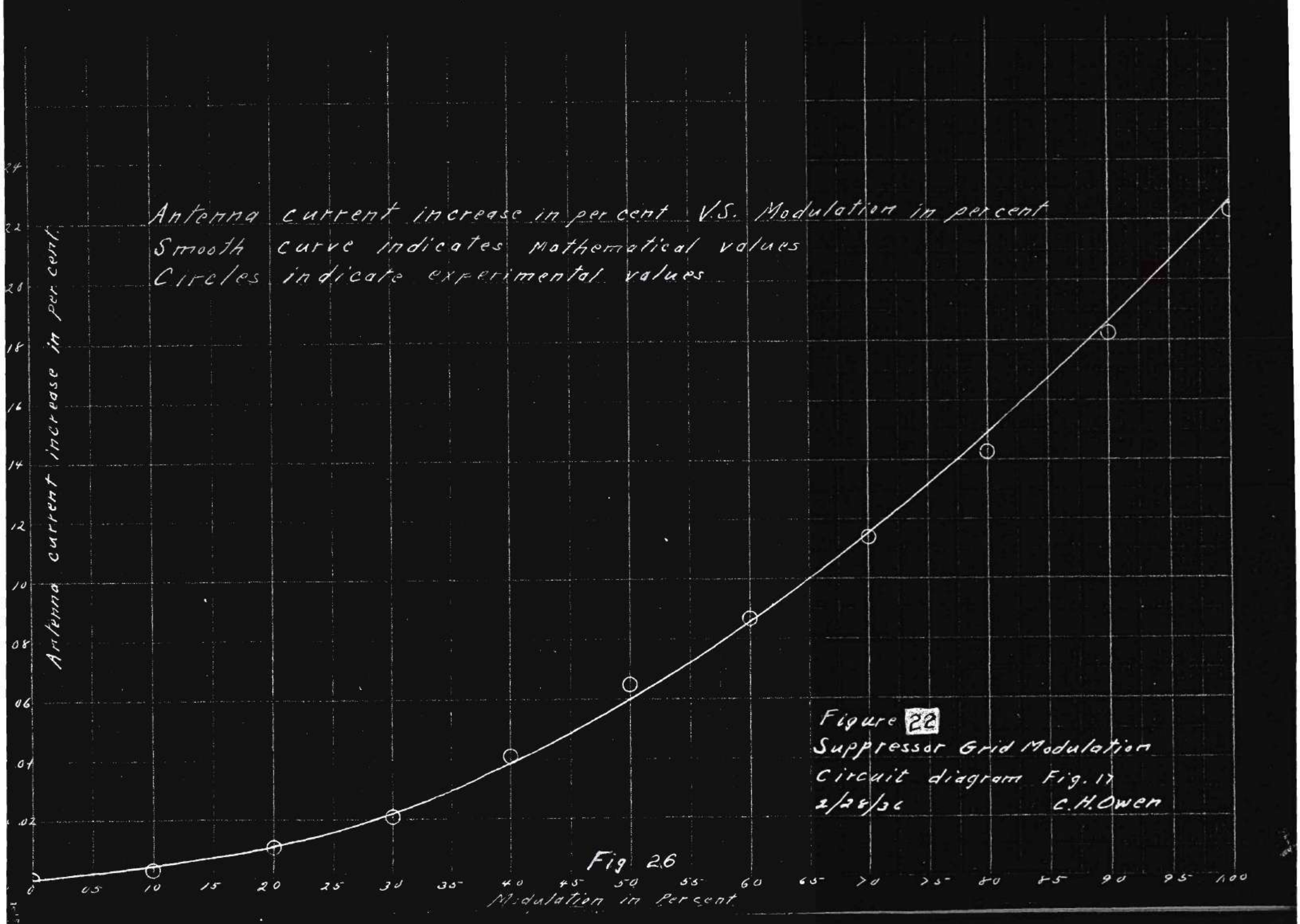


Figure 22
Suppressor Grid Modulation
Circuit diagram Fig. 17
2/28/36 C. H. Owen

Data for Figure 22

ANTENNA CURRENT

% Mod.	Unmod. MA	Mod. MA	% Increase	Mathematical Values $m = \sqrt{2\left(\frac{I_m^2}{I^2} - 1\right)}$ % Increase
100	37.2	45.5	22.3	22.4
90	34.25	40.5	18.25	18.5
80	35.1	40.1	14.25	14.9
70	35.9	40.	11.4	11.6
60	34.5	37.5	8.7	8.6
50	36.8	39.2	6.52	6.1
40	36.5	38.	4.11	3.9
30	36.5	37.25	2.06	2.2
20	36.9	37.3	1.08	1.0
10	31.7	31.8	.031	.3
0	35.	35.	0	0

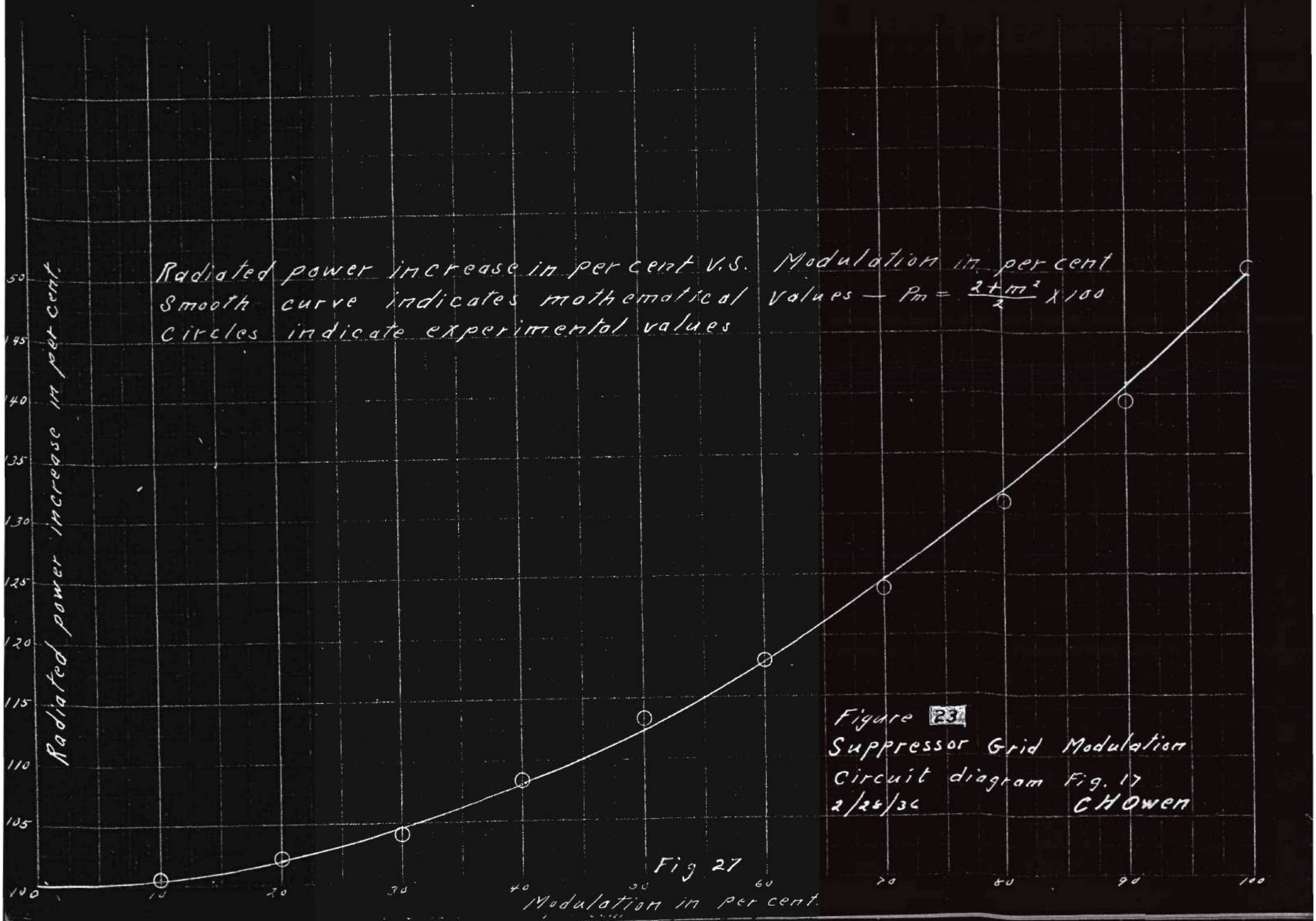


Figure 23
Suppressor Grid Modulation
Circuit diagram Fig. 17
2/26/36 C H Owen

Fig 27

Data for Figure 23

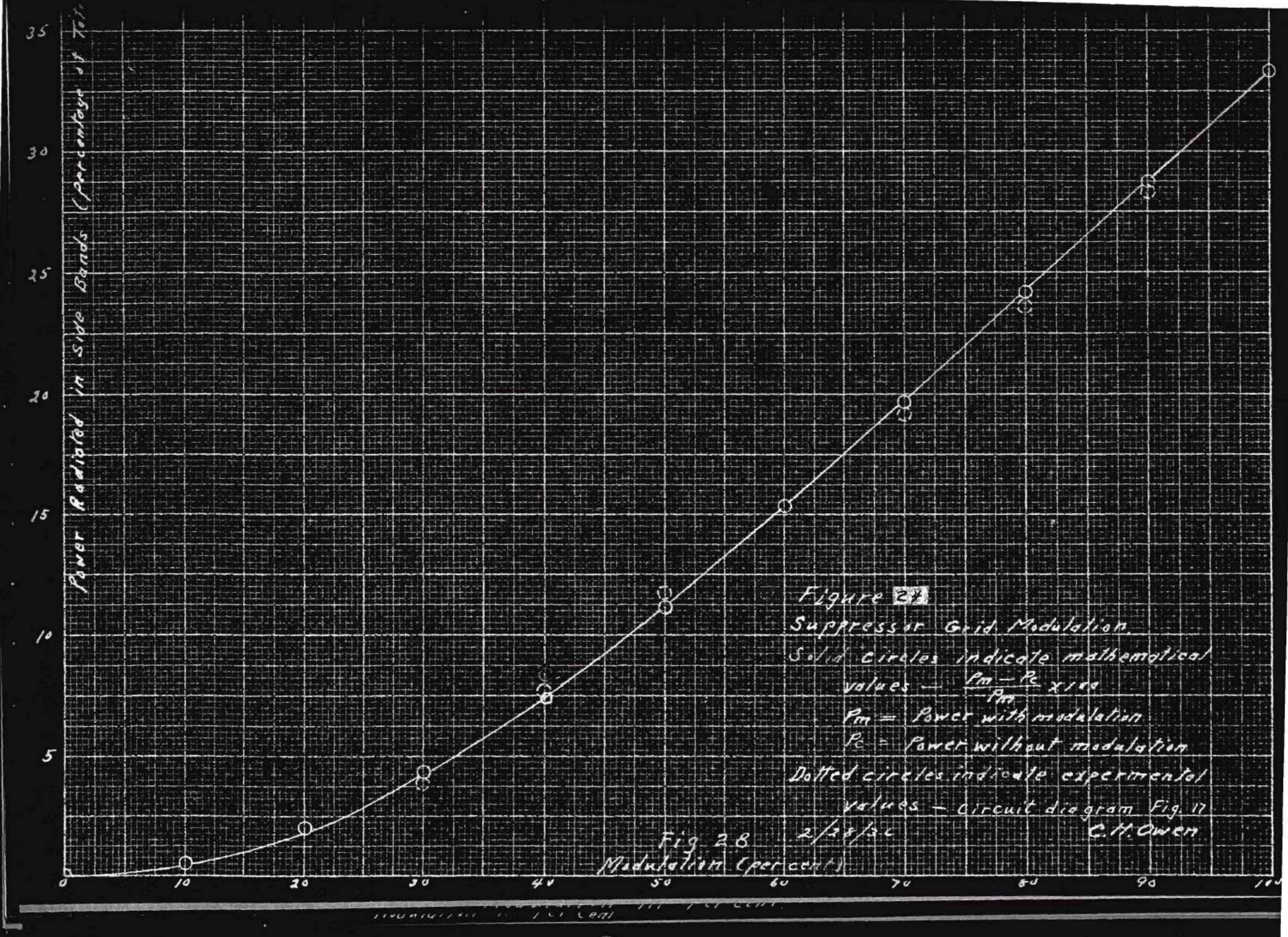
RADIATED POWER

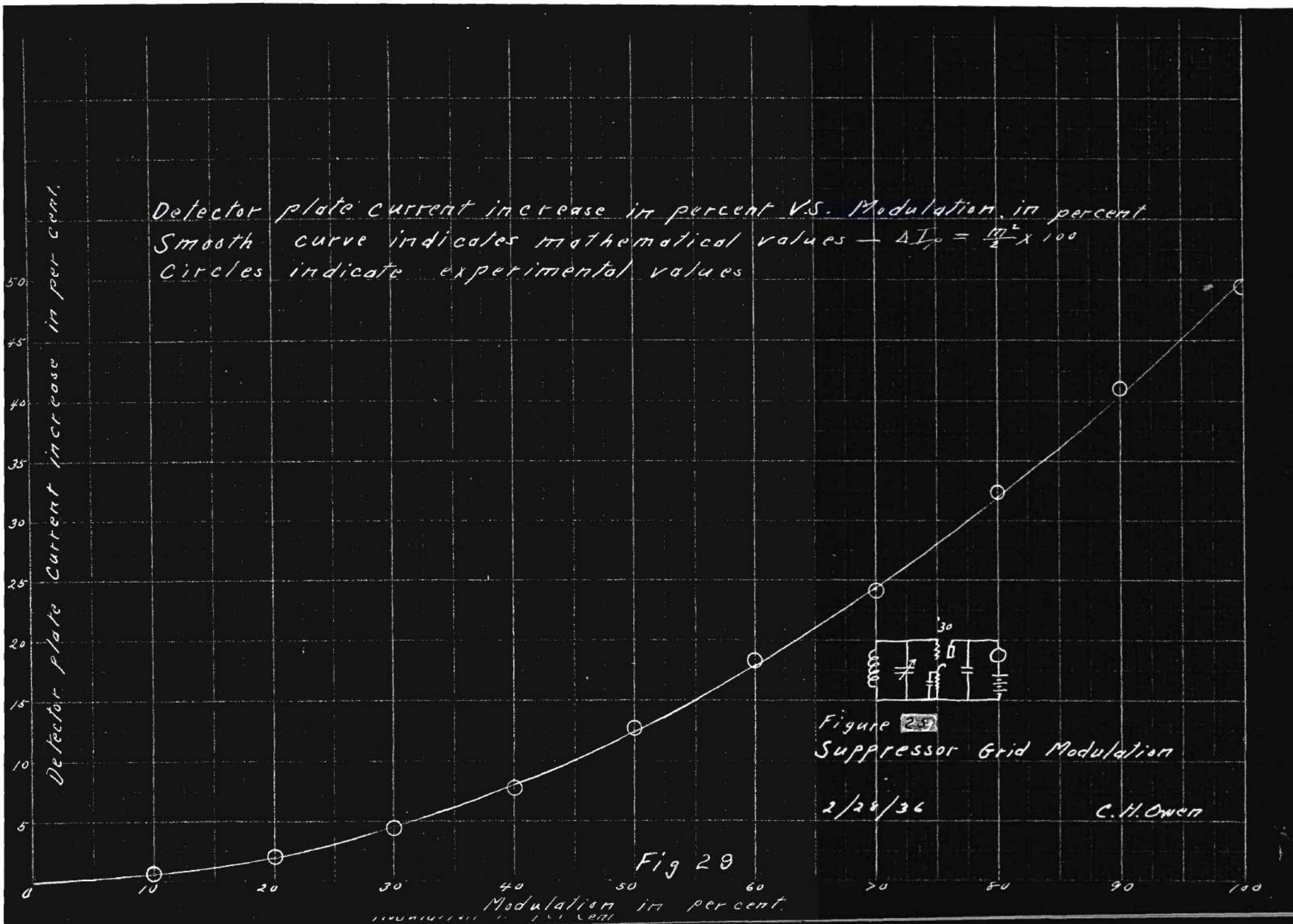
Mathematical Values

$$P_m = \frac{2 + m^2}{2} \times 100$$

% Mod.	Unmod. $W \times 10^{-3}$	Mod. $W \times 10^{-3}$	% Increase	% Increase
100	2.83	4.25	50.2	50.0
90	2.41	3.36	39.4	40.5
80	2.52	3.30	31.0	32.0
70	2.65	3.28	23.8	24.5
60	2.44	2.88	18.0	18.0
50	2.78	3.15	13.3	12.5
40	2.73	2.96	8.43	8.0
30	2.73	2.84	4.03	4.5
20	2.79	2.85	2.15	2.0
10	2.06	2.07	.53	0.5
0	2.73	2.73	.0	.0

$R_{ant.} = 2.052\ \omega$


Power Radiated in Side Bands (percentage of Tot
35
30
25
20
15
10
5
0
10
20
30
40
50
60
70
80
90
Figure 27
Suppressor Grid Modulation.
Solid circles indicate mathematical
values — $\frac{Pm - Pc}{Pm} \times 100$
Pm = Power with modulation
Pc = Power without modulation
Dotted circles indicate experimental
values — Circuit diagram Fig. 17
2/28/3c
C. H. Owen
Fig. 28
Modulation (per cent)


Detector plate current increase in percent V.S. Modulation in percent.
Smooth curve indicates mathematical values — $\Delta I_p = \frac{m^2}{2} \times 100$
Circles indicate experimental values
Detector plate current increase in per cent.
5
10
15
20
25
30
35
40
45
50
0
10
20
30
40
50
60
70
80
90
100
Modulation in percent.
30
Figure 25
Suppressor Grid Modulation
2/28/36
C. H. Owen
Fig 29

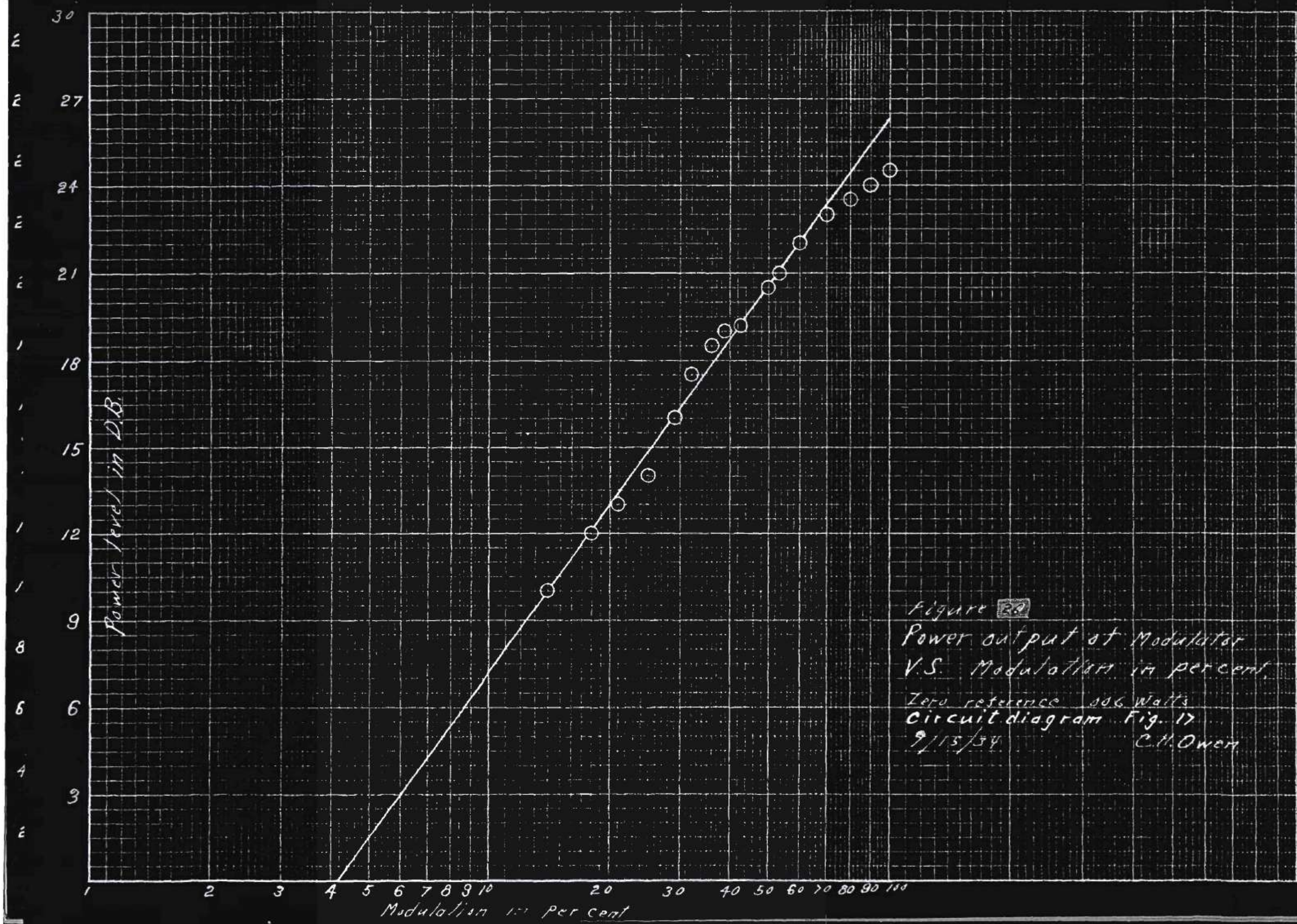


Figure 20
Power output of Modulator
V.S. Modulation in percent.
Zero reference .006 Watts
Circuit diagram Fig. 17
9/13/34 C.H. Owen

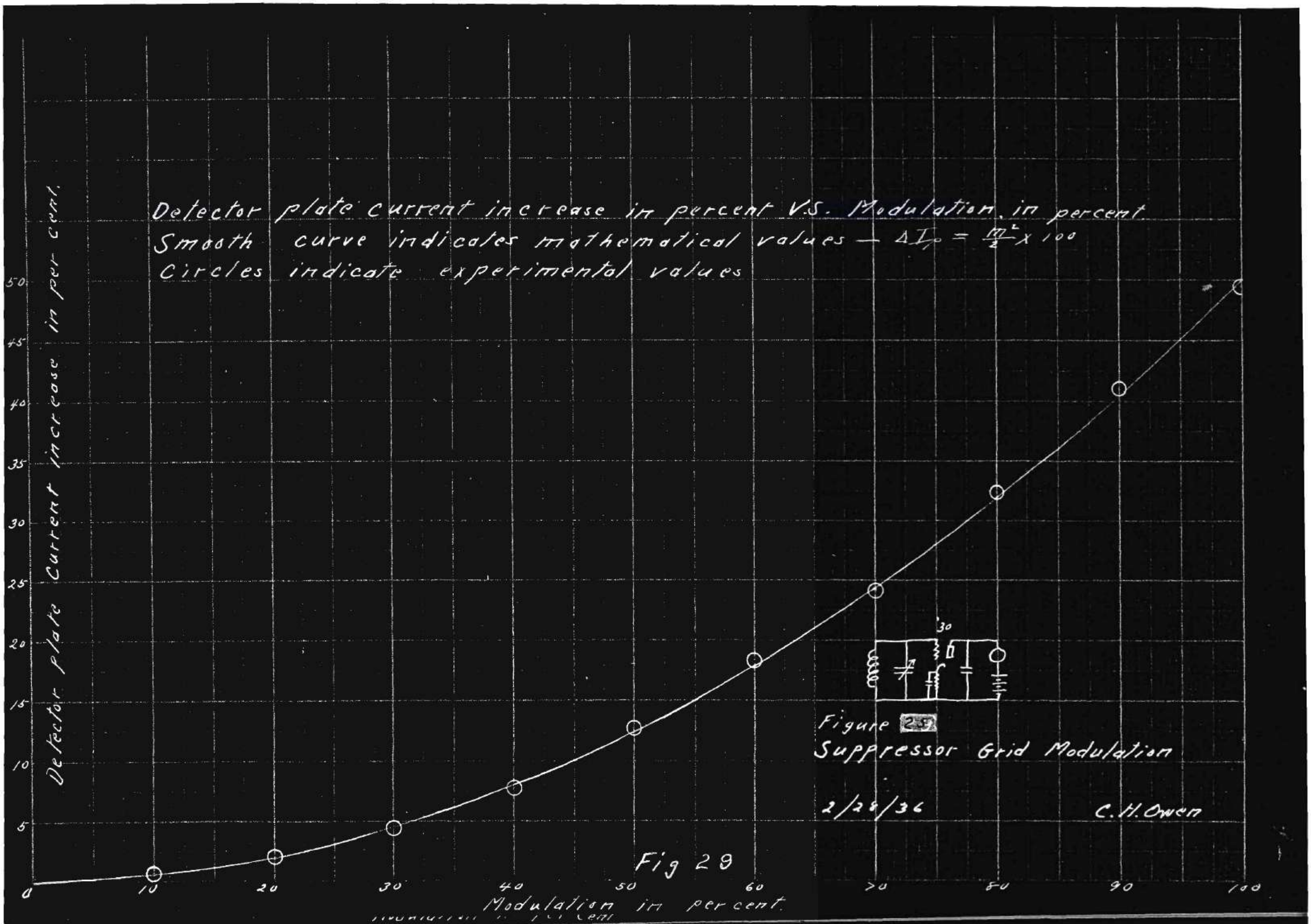
Data for Figure 24

PERCENTAGE OF POWER
RADIATED IN SIDEBANDS

Mathematical Values

$$P = \frac{m^2}{2 + m^2} \times 100$$

% Mod.	Power Unmod. $W \times 10^{-3}$	Power Mod. $W \times 10^{-3}$	% Increase $\frac{P_{mod} - P_{car}}{P_{car}} \times 100$	% Increase
100	2.83	4.25	33.4	33.3
90	2.41	3.36	28.3	28.8
80	2.52	3.30	23.6	24.2
70	2.65	3.28	19.2	19.7
60	2.44	2.88	15.3	15.3
50	2.78	3.15	11.75	11.1
40	2.73	2.96	7.75	7.4
30	2.73	2.84	3.87	4.3
20	2.79	2.85	2.1	2.0
10	2.06	2.07	0.48	0.5
0	2.73	2.73	.0	.0


Detector plate current increase in percent V.S. Modulation in percent
Smooth curve indicates mathematical values — $\Delta I_p = \frac{m^2}{2} \times 100$
Circles indicate experimental values
Detector plate current increase in per cent.
50
45
40
35
30
25
20
15
10
5
0
10
20
30
40
50
60
70
80
90
100
Modulation in percent.
30
Figure 25
Suppressor Grid Modulation
2/28/36
C. H. Owen
Fig 29

Data for Figure 25

DETECTOR PLATE CURRENT

Mathematical Values

$$\Delta I_p = \frac{m^2}{2} \times 100$$

% Mod.	Unmod. 10^{-6}A	Mod. 10^{-6}A	% Increase	% Increase
100	44.5	66.5	49.5	50.
90	41.5	58.5	41.0	40.5
80	42.0	55.6	32.4	32.
70	41.5	51.5	24.1	24.5
60	38.5	45.6	18.4	18.0
50	40.6	45.8	12.8	12.5
40	37.8	40.8	7.9	8.0
30	37.8	39.5	4.5	4.5
20	38.6	39.4	2.07	2.0
10	37.0	37.2	0.54	0.5
0	37.	37.	.0	.0

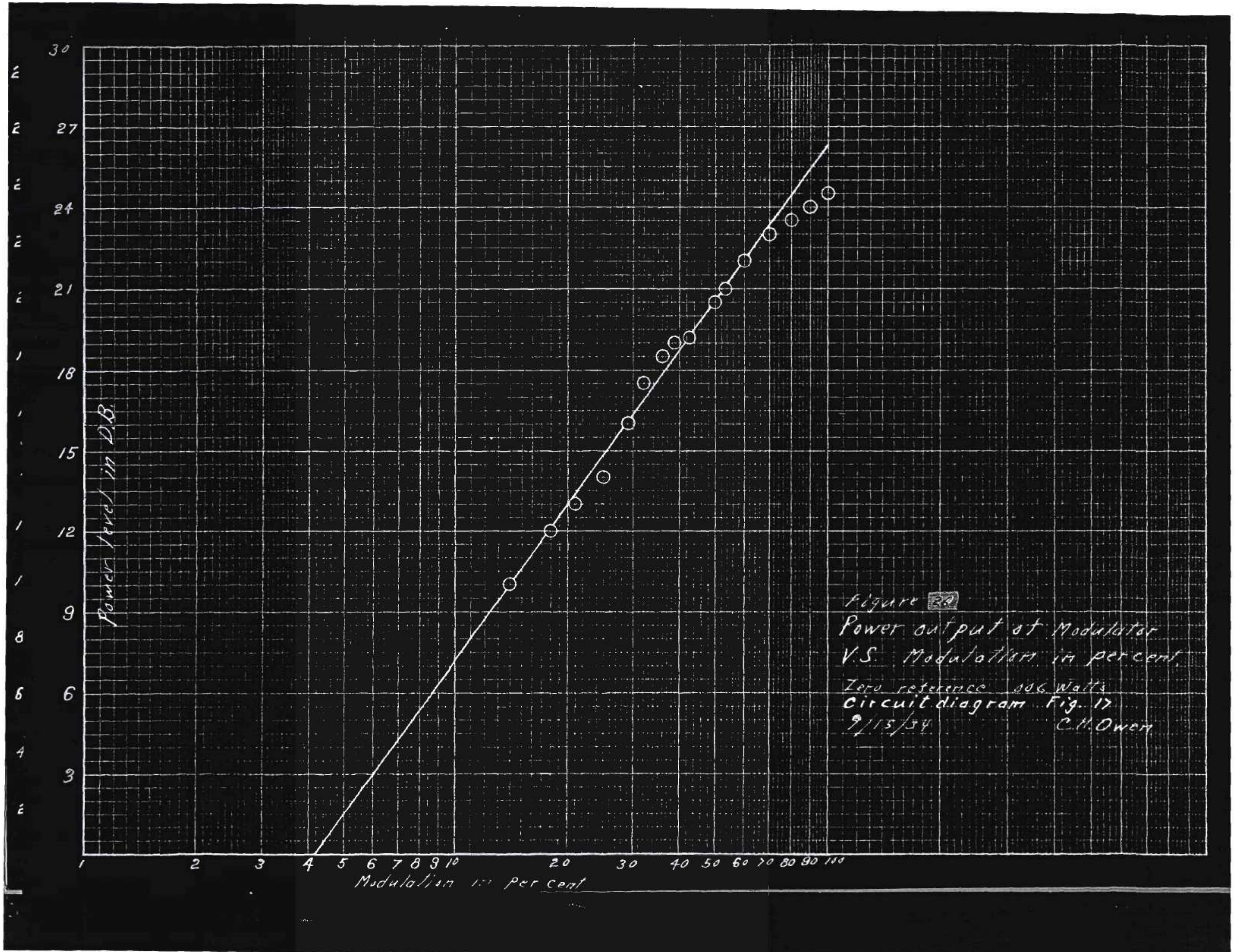
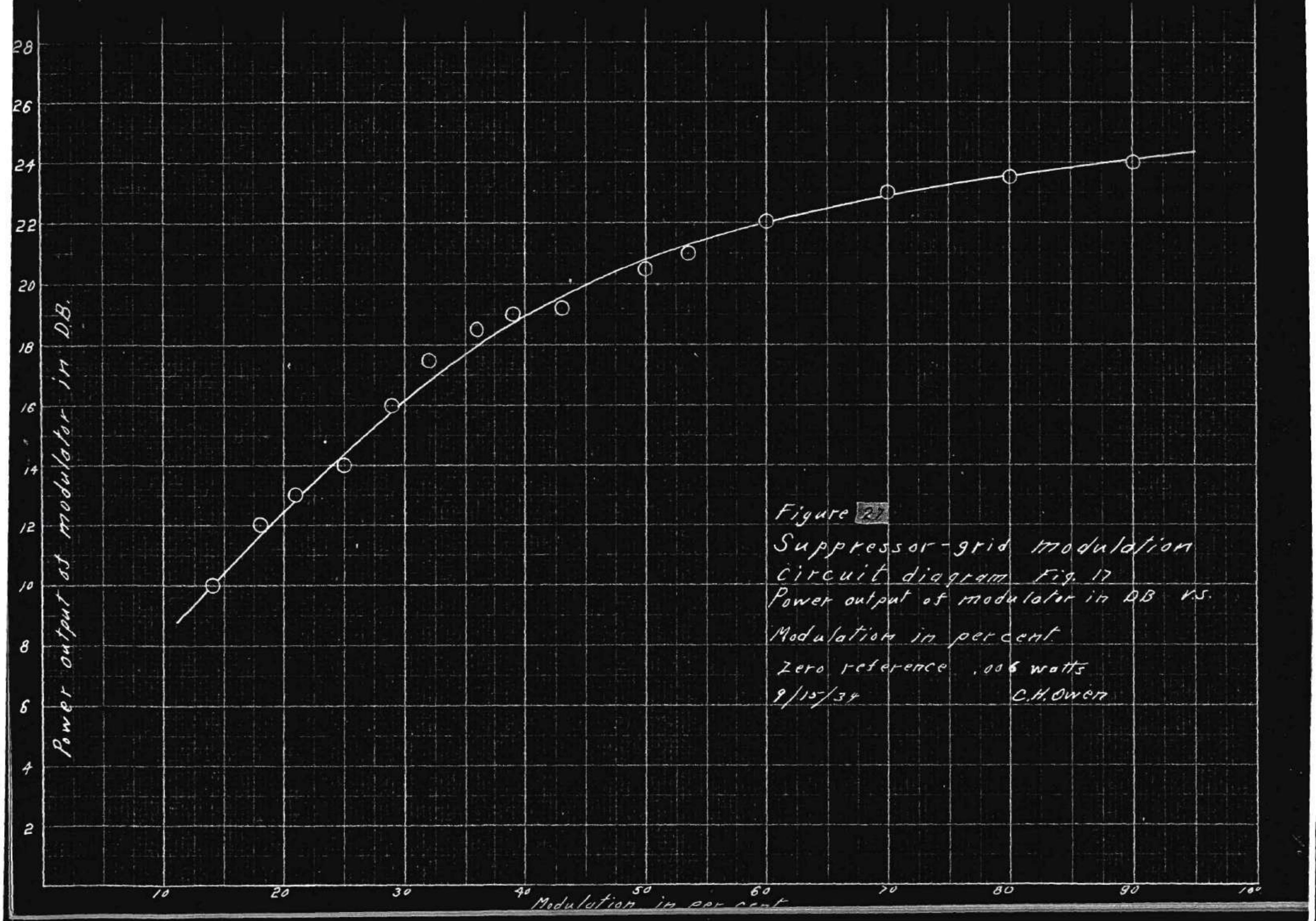


Figure 20
Power output of Modulator
V.S. Modulation in percent.

Zero reference .006 Watts
Circuit diagram Fig. 17
9/13/34 C.H. Owen



28
26
24
22
20
18
16
14
12
10
8
6
4
2
Power output of modulator in D.B.
10
20
30
40
50
60
70
80
90
100
Modulation in per cent
Figure 27
Suppressor-grid modulation
circuit diagram Fig. 17
Power output of modulator in DB V.S.
Modulation in percent
Zero reference .006 watts
9/15/34
C.H. Owen

PERCENTAGE OF MODULATION VERSUS MODULATOR POWER OUTPUT

Mod. %	Level DB
100	24.5
90	24.
80	23.5
70	23.
60	22.
53.5	21.
50	20.5
43	19.2
39	19.
36	18.5
32	17.5
29	16.
25	14.
21	13.
18	12.
14	10.

OVERMODULATION

So far in this treatise very little has been said about overmodulation except that it was something to be avoided. As a starting point it is well to define what is meant by the term "overmodulation". The term itself means that the percentage of modulation is too high. Many transmitters cannot be modulated up to 100% without serious distortion, and no transmitter can be modulated greater than 100% without distortion. To modulate any transmitter to such a degree that serious distortion results is considered overmodulation.

It has been impossible to accurately determine the percentage of modulation because adequate equipment has not been available. The most accurate type of equipment available has been the cathode ray oscillograph, and this type was only accurate to about 10% on steady tone, or perhaps about 20% on speech or music. With this oscillograph it was difficult to determine whether 90%, 100%, or 110% modulation was being obtained.

Standard engineering practice has been to set the volume control so that it "peaked" at the maximum desired "level" about once every ten seconds. This practice was adopted to avoid "over-riding" (trying to adjust all peaks to equal amplitude) the gain control of the speech amplifier, a practice which tends to destroy the naturalness of music. All peaks are not of equal amplitude to begin with, and to make them so in transmission would introduce distortion. It might be well to mention that there has been placed on the market recently a type of vacuum tube voltmeter with an extremely high speed indicator, which effectively follows the audio envelope, and is said to have a high degree of accuracy.

MEASUREMENT OF DISTORTION AS A FUNCTION OF MODULATION

With all the interest in high fidelity and high percentage of modulation now prevailing, it is interesting to observe the distortion at the various modulation levels, particularly close to 100% modulation. For these experiments the General Radio equipment owned and operated by W. J. Holey, Consulting Radio Engineer, was borrowed and operated under his direction.

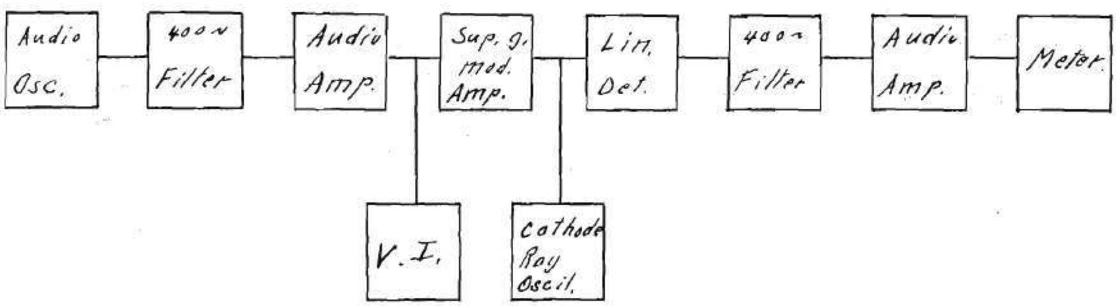


Fig 28

Figure 28 shows a block diagram of the set-up for the entire distortion measuring equipment. The audio frequency used for these experiments was 400 cycles, which is standard for this use. The output of the oscillator was passed through a filter, which filtered out everything except the 400 cycle sine wave. This sine wave was next amplified by the audio amplifier, which in this case was also the modulator. The volumn indicator indicated the audio level as delivered to the input of the suppressor-grid modulated amplifier. The antenna coil served as pick-up for the circuit feeding the cathode ray oscillograph and linear detector. The output of the linear detector was fed into the 400 cycle filter which filtered out only the fundamental or 400 cycles, allowing other frequencies to pass. The signals getting past the filter were amplified and indicated on the copper-oxide rectifying type meter. As a brief review, it is easy to see that if an audio frequency in the form of a pure sine wave is fed into the speech input of a transmitter, and the output of the transmitter is rectified by a linear detector, and then the original audio frequency filtered out, all that remained would be distortion or something added by the transmitter.

Several runs were made, the averages taken, and the following data compiled: percentage of modulation on negative peaks, percentage of modulation on positive peaks, input level in D.B., and percentage of distortion. It was noted that the percentage of modulation was not necessarily the same for the negative as for the positive peaks. This condition existed because of distortion and the inaccuracy of measuring the percentage of modulation for each peak. The curve of Figure 29 shows that although the points did not all fall on a straight line there were none very far off.

From the curves of Figures 30 and 31 it is observed that the audio power required is a logrithmic function of the percentage of modulation. It is also noted that the percentage of modulation was only taken up as high as 90%.

The reason for this was that the audio amplifier, that had previously been used as modulator, had been dismantled, and that sufficient power was not at hand to modulate the amplifier up to 100%. The linear detector used for these experiments was designed for transmitters of high power, and for that reason was not sufficiently sensitive for a transmitter of such low power. As a natural result the coupling to the tank circuit had to be made very close so that the transmitter was unduly loaded. It was believed that for this reason the distortion was high.

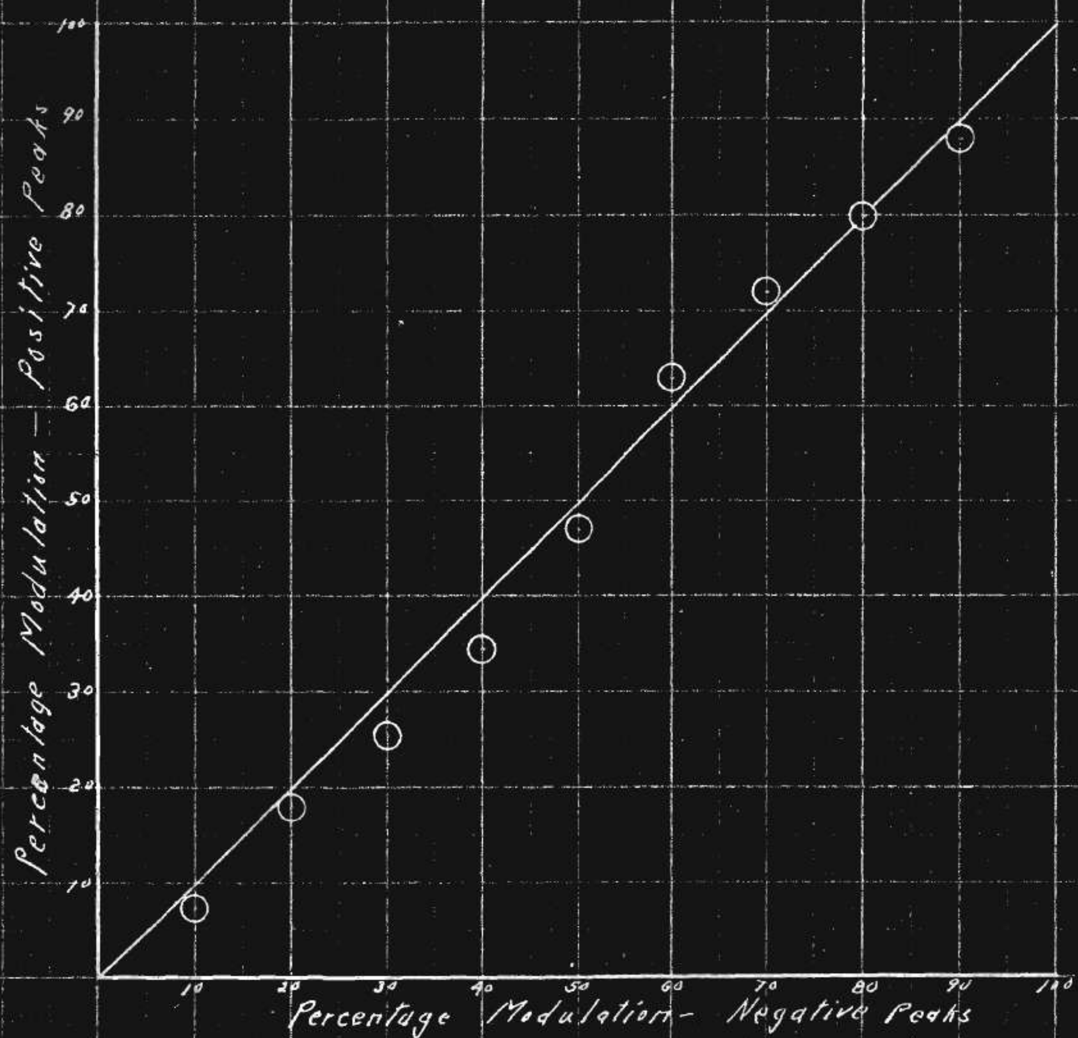


Figure 2[illegible]

Suppressor Grid Modulation

Percentage Modulation —

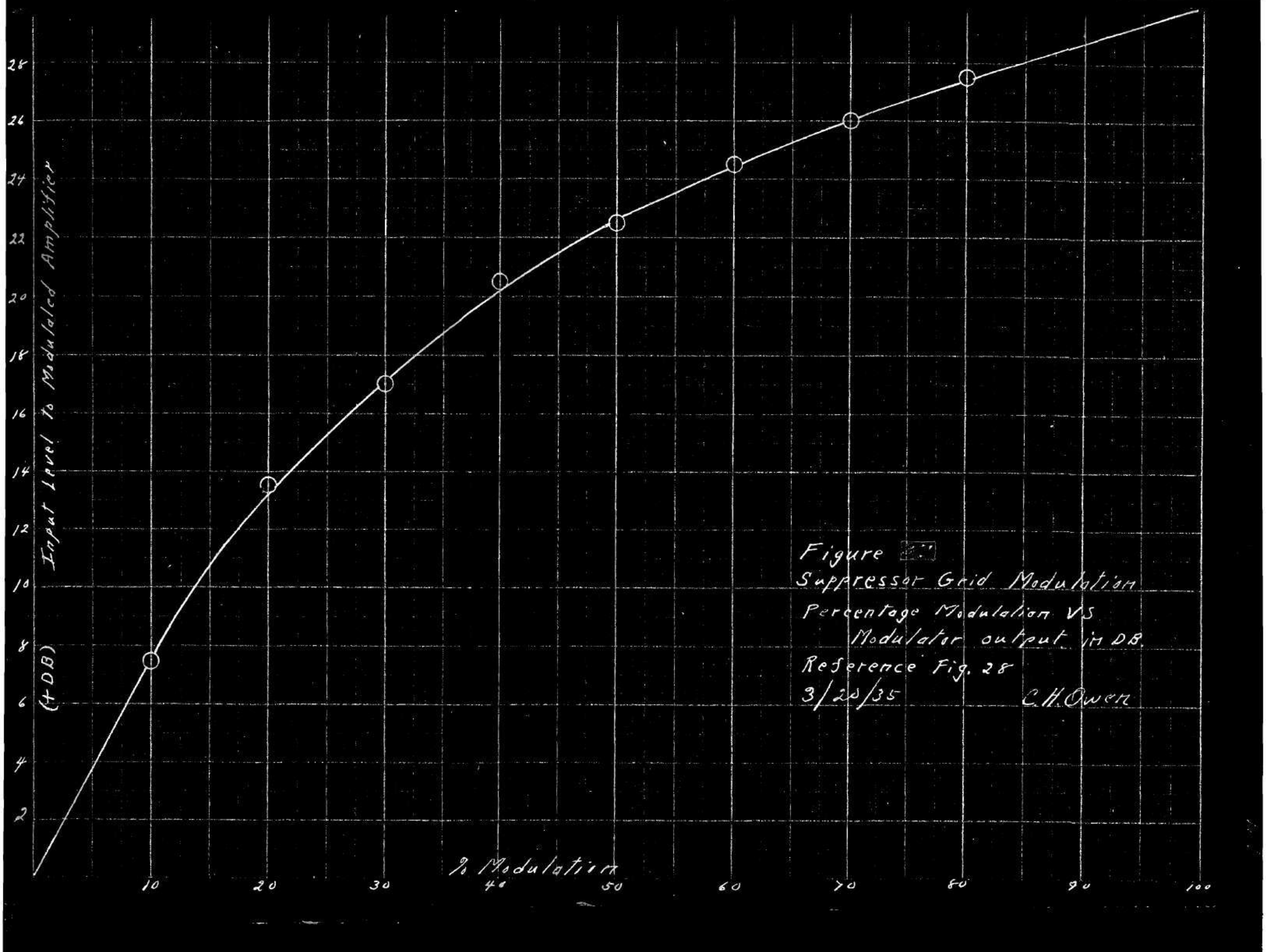
Negative Peaks VS Positive peaks

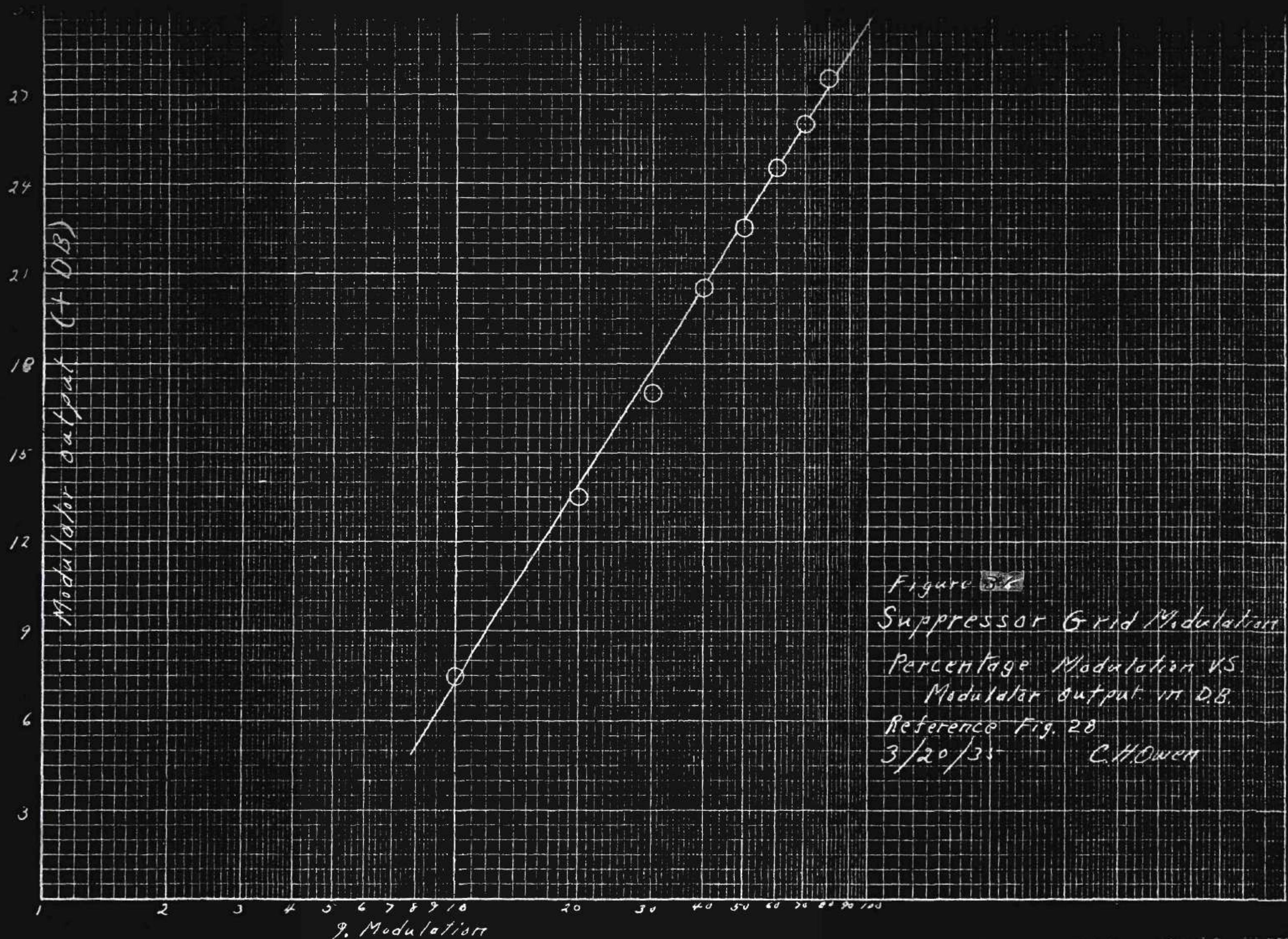
Measured with Generald Radio

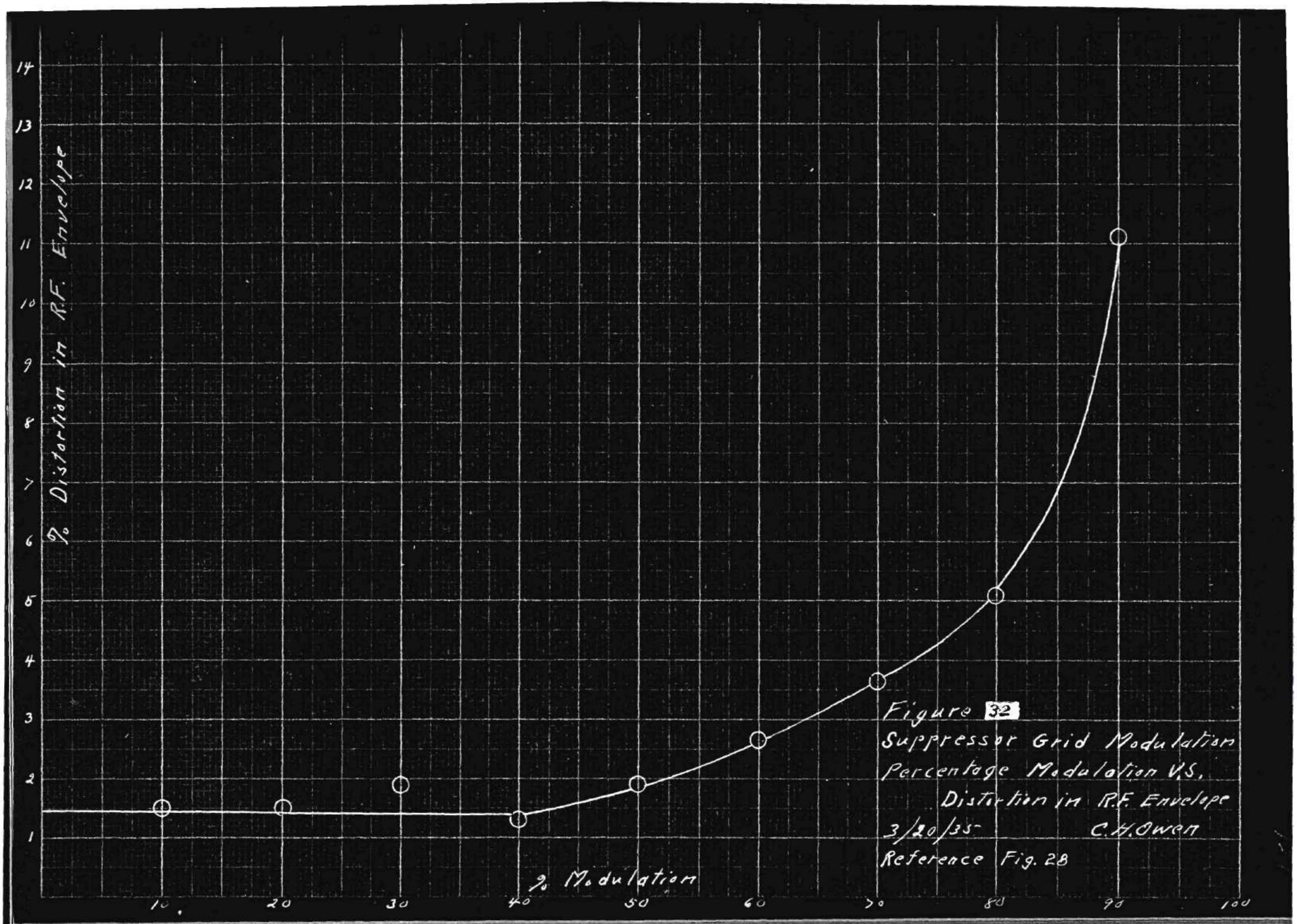
Distortion Meter.

3/18/35 C.H. Owen

Reference Fig. 28


(+DB) Input Level to Modulated Amplifier
% Modulation
2
4
6
8
10
12
14
16
18
20
22
24
26
28
10
20
30
40
50
60
70
80
90
100
Figure
Suppressor Grid Modulation
Percentage Modulation VS
Modulator output in DB.
Reference Fig. 28
3/20/35
C.H. Owen


Modulator output (+ DB)
27
24
21
18
15
12
9
6
3
1
2
3
4
5
6
7
8
9
10
20
30
40
50
60
70
80
90
100
%. Modulation
Figure 3
Suppressor Grid Modulation
Percentage Modulation V.S.
Modulator output in D.B.
Reference Fig. 28
3/20/35
C.H.Owen


% Distortion in R.F. Envelope
14
13
12
11
10
9
8
7
6
5
4
3
2
1
% Modulation
10
20
30
40
50
60
70
80
90
100
Figure 32
Suppressor Grid Modulation
Percentage Modulation V.S.
Distortion in R.F. Envelope
3/20/35
C.H. Owen
Reference Fig. 28

Data for Figures 29,30,31,&32

% Mod. Neg. Peaks	% Mod. Pos. Peaks	Input Level + DB*	Distortion %
10	7.5	7.5	1.5
20	18.	13.5	1.5
30	25.5	17.	1.9
40	34.5	20.5	1.3
50	47.	22.5	1.9
60	63.	24.5	2.65
70	72.	26.	3.65
80	80.	27.5	6.1
90	88.	31.	11.1

At 90% mod. $E_p = 280$ V

$I_p = 7.5$ MA

$E_c = 70$ V

* D.B. readings in volts rather than power.

ANALYZATION OF A SINE WAVE BY FOURIER'S SERIES

It is interesting to calculate the distortion of the audio frequency wave as delivered by the modulator. Any periodic function such as a sine wave can be represented by the use of Fourier's series as follows:

$$y = A_1 \sin\theta + A_2 \sin 2\theta + A_3 \sin 3\theta + \cdots + B_o + B_1 \cos\theta + B_2 \cos 2\theta + B_3 \cos 3\theta + \cdots \quad \text{(eq. 1)}$$

Multiply each side by sin nθ and integrate over one cycle, or 360°, and obtain:

$$\int_0^{2\pi} y \sin n\theta d\theta = \int_0^{2\pi} (A_1 \sin n\theta \sin\theta + A_2 \sin n\theta \sin 2\theta + A_3 \sin n\theta \sin 3\theta + \cdots + B_o \sin n\theta + B_1 \sin n\theta \cos\theta + B_2 \sin n\theta \cos 2\theta + B_3 \sin n\theta \cos 3\theta + \cdots) d\theta \quad \text{(eq. 2)}$$

By integration it is seen that $\int_0^{2\pi} (\sin n\theta \sin m\theta) d\theta$ is zero, unless n and m are equal, and that $\int_0^{2\pi} (\sin n\theta \cos m\theta) d\theta$ is always zero; therefore, equation 2 reduces to

$$\int_0^{2\pi} y \sin n\theta d\theta = \int_0^{2\pi} A_n \sin^2 n\theta d\theta \quad \text{(eq. 3)}$$

By integrating the right hand member we get:

$$\int_0^{2\pi} y \sin n\theta d\theta = \int_0^{2\pi} A_n \left(\frac{1}{2} - \frac{1}{2} \cos 2n\theta\right) d\theta$$

$$= A_n \left[\frac{1}{2}\theta - \frac{1}{4n} \sin 2n\theta\right]_0^{2\pi}$$

$$= \pi A_n$$

or

$$A_n = \frac{1}{\pi} \int_0^{2\pi} y \sin n\theta d\theta \quad \text{(eq. 4a)}$$

In like manner it can be shown that:

$$B_n = \frac{1}{\pi} \int_0^{2\pi} y \cos m\theta d\theta \quad \text{(eq. 4b)}$$

The amplitude of any of the harmonics is $\sqrt{A_n^2 + B_n^2}$; whereupon all A_n's or all B_n's cannot be made zero except for some types of waves.

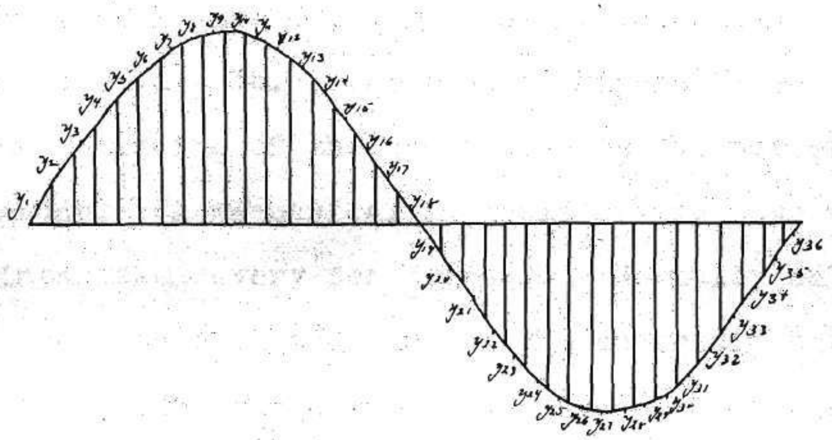


Fig. 33

The actual integration is done mechanically. Suppose the wave of Figure 33 is to be analyzed. Δ x is in this case selected to be 10°. Then the cycle is divided into thirty-six equal parts, and the total area under the curve is:

$$\int_0^{2\pi} y \, d\theta = (\Delta x)\,(y_1 + y_2 + y_3 + \cdots + y_{36}) \qquad \text{(eq. 5)}$$

As $\Delta x = \dfrac{\pi}{36}$

$$\int_0^{2\pi} y \, d\theta = \frac{\pi}{36}\,(y_1 + y_2 + y_3 + \cdots + y_{36}) \qquad \text{(eq. 6)}$$

By combining equations 3 and 6, we get:

$$A_n = \frac{1}{36}\,(y_1' + y_2' + y_3' + \cdots + y_{36}') \qquad \text{(eq. 7)}$$

Where $y' = y \sin n\theta$ Also

$$B_n = \frac{1}{36}\,(y_1'' + y_2'' + y_3'' + \cdots + y_{36}'') \qquad \text{(eq. 8)}$$

Where $y'' = y \cos n\theta$

Also

$$C_n = \sqrt{A_n^2 + B_n^2}$$

Tables have been prepared for the analysis of the wave of Figure 34, a mechanical enlargement of which is shown by Figure 35. The wave of Figure 34 was obtained by making a tracing of the audio wave on the screen of an oscillograph. A mechanical analysis of the wave was made with points taken every ten degrees. Normally only 90° or 180° would be analyzed, but as the curve did not cross the x-axis at 180° the entire sine wave of 360° was analyzed. Referring to the tables at the end of this chapter, numbered Tables No. 1, 2 and 3, the first column is the angle θ taken at 10° intervals. The second column "y" is the actual measurement along the y-axis of the curve corresponding to the angle θ. The third column is the sine of the angle θ. The fourth and fifth columns are the result of the multiplication of columns two and three. In this regard it is to be noted that the negative sign of y for the third and fourth quadrants is disregarded in determining $y \sin \theta$ of the fundamental, as the integration is to obtain the total area under the curve; therefore, the area taken when the curve is below the x-axis is added to that taken when the curve is above the x-axis. The sixth column shows the cosine of the angle θ, while the seventh and eighth columns show the result of the multiplication of columns one and seven.

$$A_1 = \frac{1388.61}{36} = 38.57$$

$$B_1 = \frac{460.39 - 506.00}{36} = \frac{45.61}{36} = 1.27$$

$$C_1 = \sqrt{A_1^2 + B_1^2} = 38.58$$

The value, C_1, is the true peak for the fundamental. It is to be noted that the cosine wave, B_1, is practically zero.

The analysis for the second harmonic is made as follows:

$$A_2 = \frac{565.2 - 602.5}{36} = 1.03$$

$$B_2 = \frac{533.1 - 519.3}{36} = .77$$

$$C_2 = \sqrt{A_2^2 + B_2^2} = 1.28$$

Analysis for the third harmonic is also made:

$$A_3 = \frac{556.5 - 589.3}{36} = .91$$

$$B_3 = \frac{540.9 - 613.3}{36} = 2.01$$

$$C_3 = \sqrt{A_3^2 + B_3^2} = 2.21$$

Higher order of harmonics than the third were not determined, because of the inaccuracies involved in obtaining the curve. These inaccuracies would arise in making a tracing of the curve, in making the mechanical enlargement, and also due to the fact that points were taken at only 10° intervals. In order to obtain accuracy for the higher order of harmonics, the points would have to be taken much closer together. It is noted that the second and third harmonics were relatively weak. It is believed that they would have been even weaker had it not been for the above mentioned inaccuracies in obtaining the curve. The final results are tabulated as follows:

	E_1	H_2	H_3	$H_{tot.}$
Values	38.58	1.28	2.21	
%		3.3	5.7	6.6

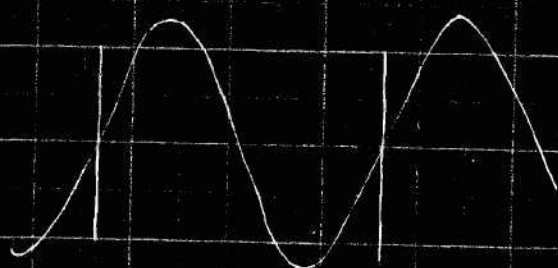


Figure 34
Sine wave on an oscillograph
3/28/36 C. H. Owen

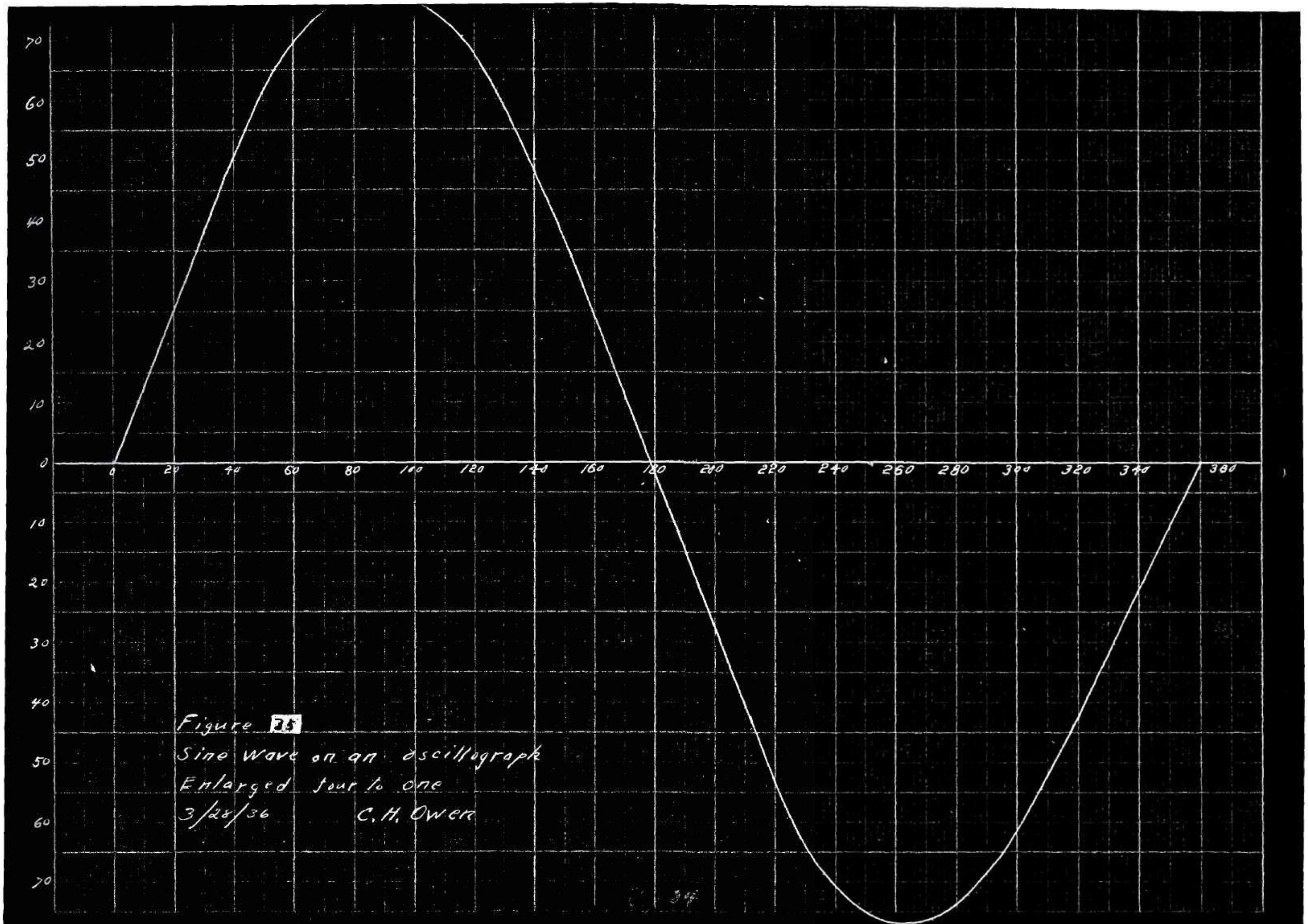


Figure 35
Sine Wave on an oscillograph
Enlarged four to one
3/28/36 C. H. Owen

Table 1

FUNDAMENTAL WAVE

θ	y	sin θ	y sin θ +	y sin θ −	cos θ	y cos θ +	y cos θ −
5	6.0	.0872	.52		.9962	5.99	
15	18.5	.2588	4.77		.9659	17.8	
25	32.0	.4226	13.7		.9063	29.0	
35	45.0	.5736	25.8		.8192	36.8	
45	56.0	.7071	39.5		.7071	39.5	
55	66.0	.8192	54.0		.5736	37.8	
65	72.5	.9063	65.5		.4226	30.5	
75	76.5	.9659	73.8		.2588	19.7	
85	78.0	.9962	77.5		.0872	6.8	
95	77.5	.9962	77.1		-.0872		6.75
105	75.0	.9659	72.3		-.2588		19.4
115	70.5	.9063	63.7		-.4226		29.7
125	63.5	.8192	51.9		-.5736		36.3
135	53.5	.7071	37.7		-.7071		37.8
145	42.5	.5736	24.3		-.8192		34.7
155	30.0	.4226	12.65		-.9063		27.2
165	17.5	.2588	4.5		-.9659		16.9
175	4.5	.0872	.39		-.9962		4.48
185	-8.5	-.0872	.74		-.9962	8.45	
195	-21.5	-.2588	5.54		-.9659	20.75	
205	-34.0	-.4226	14.35		-.9063	30.8	
215	-47.0	-.5736	26.9		-.8192	38.4	
225	-59.0	-.7071	41.6		-.7071	41.5	
235	-67.5	-.8192	55.2		-.5736	38.6	

Table 1

FUNDAMENTAL WAVE (Continued)

θ	y	sin θ	y sin θ +	y sin θ −	cos θ	y cos θ +	y cos θ −
245	-73.0	-.9063	66.1		-.4226	30.8	
255	-76.5	-.9659	73.8		-.2588	20.5	
265	-77.0	-.9962	76.6		-.0872	6.7	
275	-76.0	-.9962	75.6		.0872		6.6
285	-71.5	-.9659	69.0		.2588		18.4
295	-65.0	-.9063	58.8		.4226		27.4
305	-57.0	-.8192	46.6		.5736		32.6
315	-47.0	-.7071	33.2		.7071		33.2
325	-37.0	-.5736	21.2		.8192		30.2
335	-26.5	-.4226	11.18		.9063		24.0
345	-16.0	-.2588	4.13		.9659		15.4
355	-5.0	-.0872	.44		.9962		4.97
			1388.61			460.39	506.00

Table 2

SECOND HARMONIC

θ	y	2θ	sin 2θ	y sin 2θ		cos 2θ	y cos 2θ	
				+	−		+	−
5	6.	10	.174	1.0		.985	5.9	
15	18.5	30	.5	9.3		.866	16.0	
25	32.0	50	.766	24.5		.642	20.5	
35	45.0	70	.9396	42.2		.342	15.4	
45	56.0	90	1.0	56.0		.0	.0	.0
55	66.0	110	.9396	62.0		-.342		22.5
65	72.5	130	.766	55.5		-.642		46.5
75	76.5	150	.5	38.2		-.866		66.2
85	78.0	170	.174	13.6		-.985		76.7
95	77.5	190	-.174		13.5	-.985		76.2
105	75.0	210	-.5		37.4	-.866		65.0
115	70.5	230	-.766		54.0	-.642		45.2
125	63.5	250	-.9396		59.5	-.342		21.7
135	53.5	270	-1.0		53.5	.0	.0	.0
145	42.5	290	-.9396		39.9	.342	14.5	
155	30.0	310	-.766		23.0	.642	19.2	
165	17.5	330	-.5		8.8	.866	15.1	
175	4.5	350	-.174		.8	.985	4.4	
185	-8.5	370	.174		1.5	.985		8.4
195	-21.5	390	.5		10.8	.866		18.6
205	-34.0	410	.766		26.0	.642		21.8
215	-47.0	430	.9396		44.1	.342		16.0
225	-59.0	450	1.0		59.0	.0		.0
235	-67.5	470	.9396		63.3	-.342	23.0	

Table 2

SECOND HARMONIC (Continued)

θ	y	2θ	sin 2θ	y sin 2θ +	y sin 2θ —	cos 2θ	y cos 2θ +	y cos 2θ —
245	-73.0	490	.766		55.8	-.642	46.8	
255	-76.5	510	.5		38.2	-.866	66.0	
265	-77.0	530	.174		13.4	-.985	75.8	
275	-76.0	550	-.174	13.2		-.985	74.7	
285	-71.5	570	-.5	35.7		-.866	61.9	
295	-65.0	590	-.766	49.7		-.642	41.6	
305	-57.0	610	-.9396	53.5		-.342	19.5	
315	-47.0	630	-1.0	47.0		.0	.0	.0
325	-37.0	650	-.9396	34.8		.342		12.6
335	-26.5	670	-.766	20.2		.642		17.0
345	-16.0	690	-.5	8.0		.866		13.8
355	-5.0	710	-.174	.8		.985		4.9
				565.2	602.5		533.1	519.3

Table 3

THIRD HARMONIC

θ	y	3θ	sin 3θ	y sin 3θ		cos 3θ	y cos 3θ	
				+	—		+	—
5	6.	15	.2588	1.5		.9659	5.8	
15	18.5	45	.7071	13.0		.7071	13.0	
25	32.0	75	.9659	30.8		.2588	8.3	
35	45.0	105	.9659	43.5		-.2588		11.6
45	56.0	135	.7071	39.5		-.7071		39.5
55	66.0	165	.2588	17.0		-.9659		63.8
65	72.5	195	-.2588		18.7	-.9659		70.0
75	76.5	225	-.7071		54.0	-.7071		54.0
85	78.0	255	-.9659		75.2	-.2588		20.2
95	77.5	285	-.9659		74.8	.2588	20.0	
105	75.0	315	-.7071		52.9	.7071	53.0	
115	70.5	345	-.2588		25.2	.9659	68.0	
125	63.5	375	.2588	16.4		.9659	61.3	
135	53.5	405	.7071	37.8		.7071	37.8	
145	42.5	435	.9659	41.0		.2588	11.0	
155	30.0	465	.9659	28.6		-.2588		7.7
165	17.5	495	.7071	12.4		-.7071		12.3
175	4.5	525	.2588	1.2		-.9659		4.3
185	-8.5	555	-.2588	2.6		-.9659	8.2	
195	-21.5	585	-.7071	15.2		-.7071	15.2	
205	-34.0	615	-.9659	32.8		-.2588	8.8	
215	-47.0	645	-.9659	45.4		.2588		12.1
225	-59.0	675	-.7071	41.6		.7071		41.7
235	-67.5	705	-.2588	17.4		.9659		65.0

Table 3

THIRD HARMONIC (Continued)

θ	y	3θ	sin 3θ	y sin 3θ +	y sin 3θ −	cos 3θ	y cos 3θ +	y cos 3θ −
245	-73.0	735	.2588		18.8	.9659		70.7
255	-76.5	765	.7071		54.0	.7071		54.0
265	-77.0	795	.9659		74.3	.2588		19.9
275	-76.0	825	.9659		73.3	-.2588	19.6	
285	-71.5	855	.7071		50.5	-.7071	50.5	
295	-65.0	885	.2588		16.8	-.9659	62.7	
305	-57.0	915	-.2588	14.7		-.9659	55.0	
315	-47.0	945	-.7071	33.2		-.7071	33.2	
325	-37.0	975	-.9659	35.7		-.2588	9.5	
335	-26.5	1005	-.9659	25.6		.2588		6.8
345	-16.0	1035	-.7071	11.3		.7071		11.3
355	-5.0	1065	-.2588	1.3		.9659		48.4
				556.5	589.3		540.9	613.3

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